Ring-shear test data of wheat flour used for analogue experiments at the Institute of Geophysics of the Czech Academy of Science, Prague

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2. Citation

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3. Data Description

This dataset provides friction data from ring-shear tests (RST) for wheat flour used as a fine-grained, cohesive analogue material for simulating brittle upper crustal rocks in the analogue laboratory of the Institute of Geophysics of the Czech Academy of Science (IGCAS). It is characterized by means of internal friction coefficients μ and cohesion *C*.

According to our analysis the materials show a Mohr-Coulomb behaviour characterized by a linear failure envelope. Peak friction coefficients μ_P of the tested material is ~0.72, dynamic friction coefficients μ_D is ~0.67 and reactivation friction coefficients μ_R is ~0.70. Cohesions of the material range between 27 and 50 Pa. The material shows a minor rate-weakening of ~1.5% per ten-fold change in shear velocity *v* and a stick-slip behaviour at low shear velocities.

3.1. Material tested

The measured material is a wheat flour type T 530 by the company Pejšův mlýn Sedlčany spol. s r.o. (http://www.pejsuvmlyn.cz). In the laboratory of the IG CAS, the wheat flower is used as material for simulating rocks with high cohesion and low density in experiments dealing with, for instance, caprock deformation of salt extrusions and host rock of magmatic intrusions. The material has a bulk density of c. 635 kg m^{-3} when poured. The grain size of wheat flour of the same type (T 530) is defined by a decree of the Ministry of Agriculture of the Czech Republic No. 333/ 97 Sb. Accordingly, the grain size is smaller than ~260 μ.

3.2. Measurement procedure

The data presented here are derived by ring shear testing using a SCHULZE RST-01.pc (Schulze, 1994, 2003, 2008) at the Helmholtz Laboratory for Tectonic Modelling (HelTec) of the GFZ German Research Centre for Geosciences in Potsdam. The RST is specially designed to measure friction coefficients μ and cohesions C in loose granular material accurately at low confining pressures and shear velocities similar to sandbox experiments. In this tester, a sand layer is sheared internally at constant normal stress σ_N and shear velocity v while shear force and lid displacement (corresponds to volume change ΔV) are measured continuously. For more details see Klinkmüller et al. (2016) and Ritter et al. (2016).

3.2.1. Sample preparation and test conditions

Each sample is carefully prepared by the same person and measured consistently following the same protocol. The measurements presented here correspond to internal friction, i.e. shearing inside the material. Preparation includes pouring into a shear cell of type No. 1. The bulk density reached with this procedure has been 635 kg/m³. Normal force, shear force, shear velocity and lid displacement are measured at 100 Hz and then down sampled to 5 Hz. Laboratory conditions are air conditioned during all the measurements (temperature: 21°C, humidity: 40%). The tests has been conducted under the Lab-ID 512-01 (RST) and 513-01 (VST) (Table 1).

3.2.2. RST (Ring-shear test) procedure

During RST a shear velocity of v = 30 mm min^{-1} and a normal load as defined below are imposed while shear force and lid displacement are measured. 12 individual tests are done at normal stresses of σ_N = 250, 500, 1000 and 2000 Pa (with 3 repetitions per stress level). During the measurement the material is sheared for initially 3 minutes. During this period the shear stress τ reaches a peak (= peak friction) and then drops to a plateau indicating shear has localized into a shear zone (= dynamic friction). The sample is then unloaded by shortly reversing rotation and immediately re-sheared for 3 minutes during which shear stress τ reaches a second peak (= reactivation friction) simulating reactivation of an existing shear zone before returning to the plateau.

3.2.3. VST (Velocity stepping test) procedure

To determine the dependence of friction on the shear velocity v, a velocity stepping test (VST) is performed. During VST shear velocities ranging from 0.1 to 30 mm min^{-1} and a normal stress of σ_N = 2000 Pa are imposed. Velocity is systematically decreased in logarithmic steps of individual time lengths adapted to the respective velocity to reach a comparable displacement of 10 mm in each step (Table 3). The velocity steps are applied after having reached the plateau of the dynamic friction.

Table 1: Sample overview *(GFZ = German Research Centre for Geosciences in Potsdam)*

GFZ-ID	Material	Preparation	Bulk density (kg/m³)	Raw data file name	Product file name
512-01	Wheat flour	poured	634	51201_XY_[f=5.00Hz][date_time] (XY = 1 … 12)	512-01_WheatFlour_Prague_RST
513-01	Wheat flour	poured	636	51301_01_[f=5.00Hz][date_time]	513-01_WheatFlour_Prague_VST

Table 2: *Logarithmic steps of the shear velocity v in a VST including the duration of each step.*

Shear velocity [mm min^{-1}]	**Period [hh:mm:ss]**
30	00:00:20
10	00:01:00
3	000:03:20
1	000:10:00
0.3	00:33:20
0.1	01:40:00

3.3. Analysis methode

3.3.1. RST analysis: Friction coefficients and cohesion

After converting forces to stresses and time to displacement, three characteristic values (strengths) have been picked manually from the resulting shear stress curves (see e.g. Figure 1):

(1) The shear strength τ^* at ***peak friction*** corresponding to the first peak in the shear curve reflecting hardening-weakening during strain localization
(2) the shear strength τ^* at ***dynamic friction*** corresponding to the plateau after localization and representing friction during sliding
(3) the shear strength τ^* at ***reactivation friction*** corresponding to the second peak and representing static friction during reactivation of the shear zone.

We performed regression analysis of these friction data by means of linear regression in two ways:

(1) A linear regression through all data pairs of shear strength τ^* and normal stress σ_N. The slope of the linear regression corresponds to the friction coefficient μ and the y-axis intercept to cohesion C (see e.g. Figure 2). This method assumes that the material behaves strictly as a Mohr-Coulomb material, i.e. has a linear failure envelope.

(2) Calculating all possible two point slopes (friction coefficient μ) and y-axis intercepts (cohesion C) for mutually combined data pairs of shear strength τ^* and normal stress σ_N. These data (i.e. all individual μ and C) are then evaluated by means of univariate statistics by calculating mean and standard deviation and comparing the probability density function (pdf) to that of a normal distribution (see e.g. Figure 3). This method overcomes the limitation of the analysis to Mohr-Coulomb material and allows for non-linear failure envelopes (Santimano et al., 2015).

In case values for μ and C as derived from the two methods are identical (within standard deviation), the material is properly characterized by a straight Mohr-Coulomb failure envelope.

3.3.2. VST analysis: Rate-dependencies of dynamic friction

From the time-series data shear stresses τ are plotted as a function of log(v) (Figure 4). The slope of a linear regression through the data approximates the dependency of the dynamic friction on the shear velocity v (i.e. its rate-dependency).

3.3.3. Python-based analysis and visualization

The data is analyzed and visualized using the custom software RST-Evaluation v.0.3.0 (https://gitext.gfz-potsdam.de/analab-code/rst-evaluation/-/tags/0.3.0) (Rudolf and Warsitzka, 2019). The open source software package provides the necessary scripts to automatically pick and select the various points of interest in the stress curves. A short description of the software and how to run it is provided in the repository. The current version uses a user interface to provide a straightforward interaction with the software and does not require that the files are stored in specific folders.

4. File description

There exist the following files in the folder "2022-016_Warsitzka-et-al_Data":

(i) RST raw data ("512-01_XY_[f=5.00Hz][date_time].tdms")
(ii) RST shear curve data ("512-01_WheatFlour_Prague_RST_ts.txt"; example Table 3)
(iii) RST shear curve plot ("512-01_WheatFlour_Prague_RST_ts.pdf"; example Figure 1)
(iv) RST friction data ("512-01_WheatFlour_Prague_RST_peak.txt", "File name_dynamic.txt", "512-01_WheatFlour_Prague RST_reactivation.txt"; example Table 4)
(v) RST friction plot and linear regression data ("512-01_WheatFlour_Prague RST_linregr.pdf", "512-01_WheatFlour_Prague_RST_fricstd.txt"; example Figure 2)
(vi) RST histograms of friction data and mutual linear regression data ("512-01_WheatFlour_Prague_RST_hist.pdf", "512-01_WheatFlour_Prague RST_fricmut.txt"; example Figure 3)
(vii) VST raw data ("513-01_01_[f=5.00Hz][date_time].tdms")
(viii) VST plot ("513-01_WheatFlour_Prague_VST.pdf"; example Figure 4)

An overview of all files of the data set is given in the 2022-016_Warsitzka-et-al_List_of_files.pdf".

4.1. RST shear curve data

RST shear curve data are derived from RST raw data (i) and given as (ii) time series (ts) data in .txt-format (“512-01_WheatFlour_Prague_RST_ts.txt”) and visualized as (iii) shear stress τ versus shear displacement d plots (“512-01_WheatFlour_Prague_RST_ts.pdf”) (Figure 1).

Table 3: Example of shear curve time series data (452-01). *First line is header. First column is time (in s). Columns 2-13 are shear forces (in N) for corresponding normal stresses as specified in the header of the respective columns (4 stress levels from 250 to 2000 Pa, three repetitions each stress level).*

Time [s]	500	1000	2000	…
0.0	1.38	-1.42	4.30	…
0.2	…	…	…	…
…	…	…	…	…

4.2. RST friction data and analysis

Friction data are given as (iii) data pairs (normal stress σ_N and shear strength τ*; Table 4) for peak, dynamic and reactivation friction in txt format (“512-01_WheatFlour_Prague RST_peak.txt”, “512-01_WheatFlour_Prague RST_dynamic.txt”, “512-01_WheatFlour_Prague RST_reactivation.txt”). They are visualized by (iv) plotting into Mohr Space (normal stress σ_N vs. shear stress τ) including a linear regression (“512-01_WheatFlour_Prague _RST_linregr.pdf”; Figure 2), while the data is additionally given in .txt-format (“512-01_WheatFlour_Prague _RST_fricstd.txt”). The results of the regression analysis (see 2.3) are plotted in (v) histograms for friction coefficients μ and cohesions C (“512-01_WheatFlour_Prague _RST_hist.pdf”; Figure 3), with the data additionally given in .txt-format (“512-01_WheatFlour_Prague _RST_fricmut.txt”).

Table 4: Example of friction data (452-01, peak). *First line is header. First column is normal stress σ_N (in Pa). Second column is shear strength τ*(in Pa).*

Normal stress [Pa]	Shear strength [Pa]	Stddev.Shear strength [Pa]
500	402	10
1000	790	11
…	…	…

4.3. VST data analysis

VST raw data (vi, “513-01_01_[f=5.00Hz][date_time]_VST.tdms”) are visualized (vii) by plotting shear velocity v and dynamic friction (simplified as shear stress τ divided by normal stress σ_N) against the shear displacement d (“513-01_WheatFlour_Prague_VST.pdf”; Figure 4). Note, that friction can be systematically overestimated here because cohesion is not considered. For analysis, the 20 percentile “fit data” of dynamic friction is plotted against the shear velocity v including a logarithmic curve fit, the slope of which reflects the rate dependency of dynamic friction.

5. Results

Our analysis reveals that the tested materials behave as a Mohr-Coulomb material characterized by a linear failure envelope. Values of friction coefficients *μ* and cohesions *C* are listed in Table 5. According to our analysis the materials show a Mohr-Coulomb behaviour characterized by a linear failure envelope. Peak friction coefficients μ_P of the tested material is ~0.75, dynamic friction coefficients μ_D is ~0.60 and reactivation friction coefficients μ_R is ~0.64. Cohesions of the material range between 90 and 130 Pa. A minor rate-weakening of ~1.5% per ten-fold change in shear velocity *v* is evident (Figure 4). The material shows a stick-slip behaviour at a shear velocities of 0.1 mm min^{-1}.

Table 5: Summary of RST data

Parameter	Symbol	Unit	Linear least-squares regression method		Mutual two-point regression method	
			Value	Standard deviation	Value	Standard deviation
Coefficient of peak friction	μ_P	-	0.715	0.005	0.72	0.05
Peak cohesion	C_P	Pa	50	5	45	50
Coefficient of dynamic friction	μ_D	-	0.666	0.006	0.68	0.07
Dynamic cohesion	C_D	Pa	41	6	27	72
Coefficient of reactivation friction	μ_R	-	0.697	**0**.007	0.70	0.08
Reactivation cohesion	C_R	Pa	57	7	34	63
Rate dependency	$\Delta\mu_D/\Delta logv$	-	-0.0151	0.00289	n.a.	n.a.

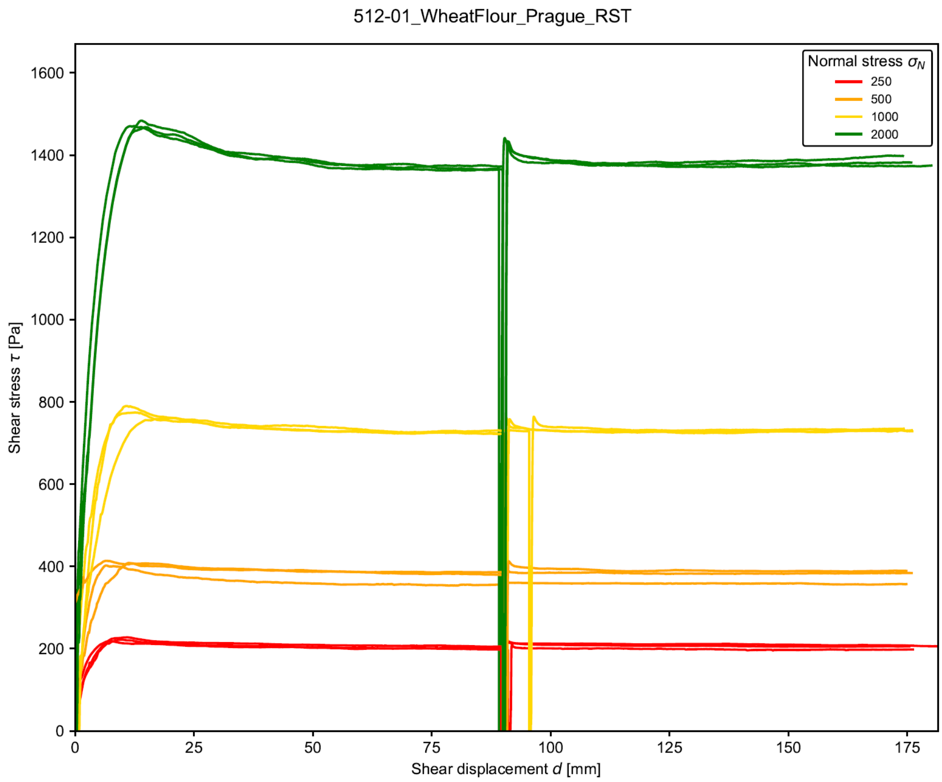

Figure 1: Example of shear curve plot (512-01). *Y-axis is shear stress τ, x-axis is shear displacement d. Each data set consists of 12 shear curves corresponding to 4 levels of normal stress σ_N with 3 repetitions each stress level.*

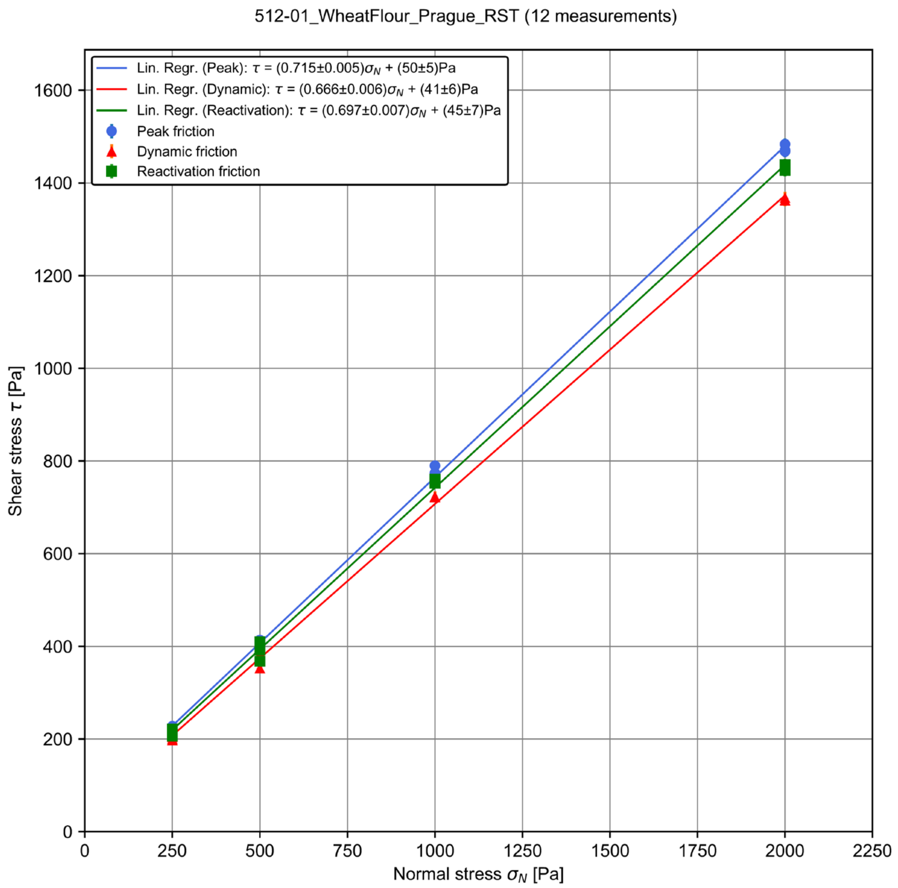

Figure 2: Example of friction plot (512-01). *Plot of all data pairs in the Mohr space (normal stress σ_N vs. shear stress τ) including curves of the corresponding linear least-squares regression.*

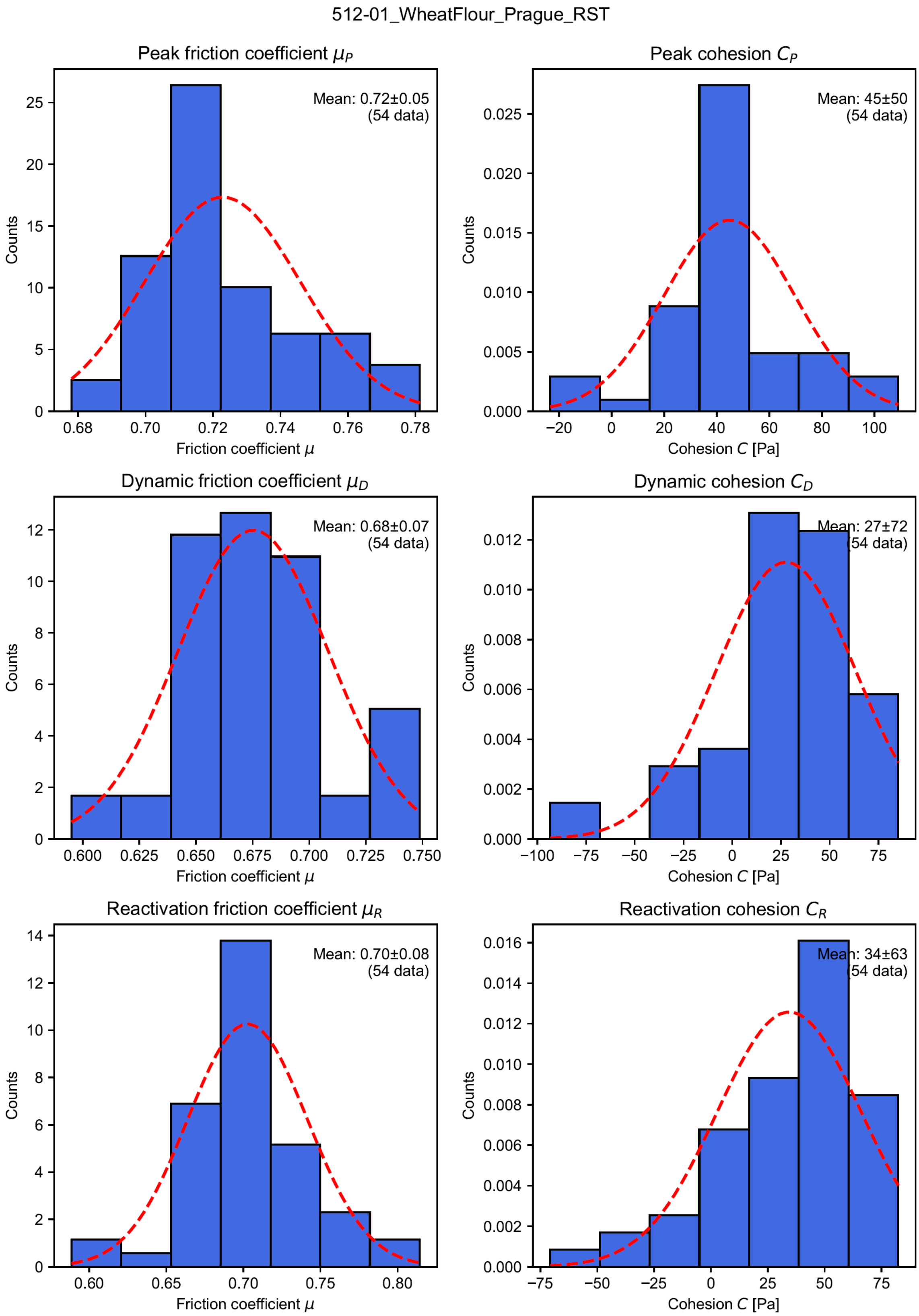

Figure 3: Example of histogram plot (512-01). *Histograms of mutual two-point regression results for slope (friction coefficient μ) and y-axis intercept (cohesion C). Red curves are synthetic normal distributions with the same mean and standard deviation (std.) as the data set for comparison.*

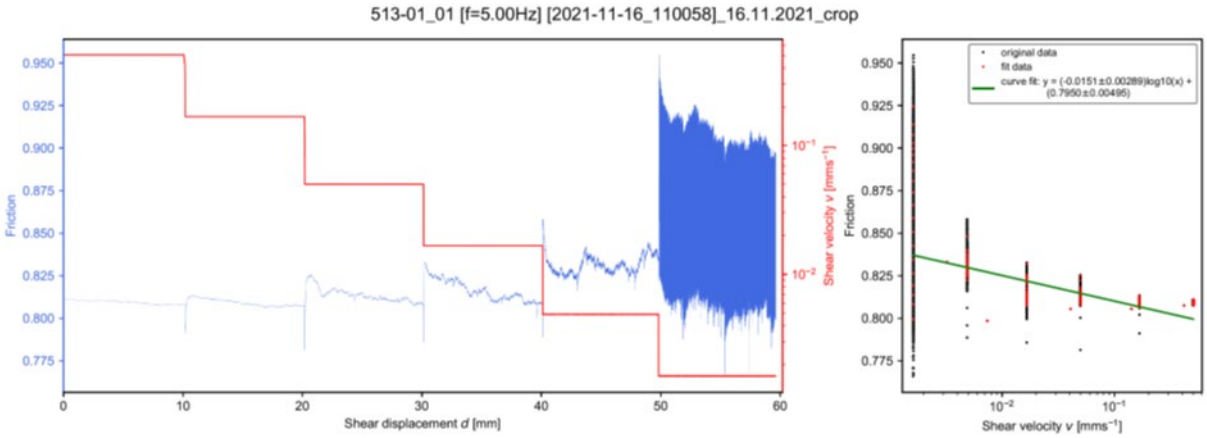

Figure 4: Example of the visualization of the VST data (513-01). *The shear velocity v is decreased stepwise (red curve), while the dynamic friction (shear stress τ/normal stress σ_N) is measured (blue curve). The logarithmic fit (green curve) reflects the slight decrease of the friction with increasing shear velocity v.*

6. References

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