Ring-shear test data of foam glass beads used for analogue experiments in the Helmholtz Laboratory for Tectonic Modelling (HelTec) at the GFZ German Research Centre for Geosciences in Potsdam and the Institute of Geoscience, Friedrich Schiller University Jena (http://doi.org/10.5880/GFZ.4.1.2019.002)

1. Citation

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2. Data Description

This dataset provides friction data from ring-shear tests (RST) for two types of foam glass beads and a mixture of foam glass beads with quartz sand ("G12"; Rosenau et al., 2019). These materials have been used in analogue experiments in Helmholtz Laboratory for Tectonic Modelling (HelTec) at the GFZ German Research Centre for Geosciences in Potsdam and in the Analogue laboratory of the Institute of Geosciences of the Friedrich Schiller University of Jena (FSU Jena). The materials have been 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 all tested materials range between 0.70 and 0.75, dynamic friction coefficients μ_D between 0.52 and 0.55 and reactivation friction coefficients μ_R between 0.60 and 0.62. Peak cohesions C_P of all materials are negative indicating that they are cohesionless. All materials show a minor rate-weakening of ~1% per ten-fold change in shear velocity v.

2.1. Materials tested

The foam glass beads consist of oval, rounded grains of foamed glass. Two types of this material have been tested, type 1 has a grain-size of 0.1-0.3 mm and type 2 has a grain size of 0.25-0.5 mm (Table 1). They are sold under the name "Blähglasgranulat" and the product IDs "Liaver 0.1-0.3mm" and "Liaver 0.25-0.5mm", respectively, by the company Liaver GmbH & Co KG (www.liaver.com). Furthermore, a mixture of foam glass beads type 1 and quartz sand "G12" (grain size = 0.1-0.4 mm) with a weight ratio 1:3 was tested. The quartz sand is used as standard analogue material for simulating brittle upper crustal rocks in the HelTec and its ring shear test data are presented in Rosenau et al. (2019). The grain density of the foam glass beads is ρ = ~800 kg m^{-3}. Bulk densities of the sieved materials are ρ = 530 kg m^{-3} for type 1, ρ = 340 kg m^{-3} for type 2 and ρ = 1140 kg m^{-3} for the mixture.

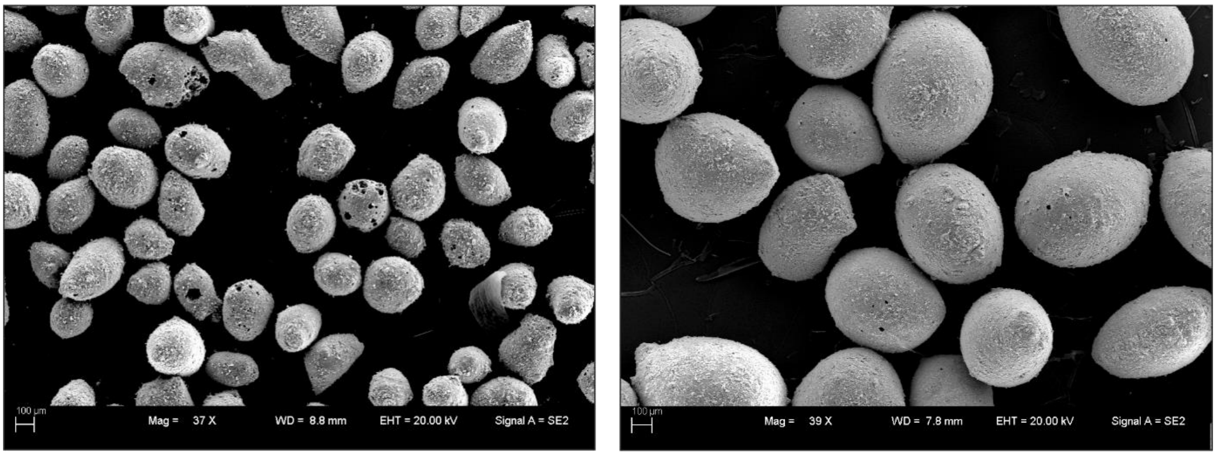

Figure 1: Examples of scanning electron microscope (SEM) images *of the tested foam glass beads 0.1-0.3 mm (left) and foam glass beads 0.25-0.05 (right). SEM images were produced using a scanning electron microscope at the Institute of Geosciences of the FSU Jena in 2014. Samples were prepared according to the lab's standard routines. Additional images can be found in the attached data repository.*

Table 1: Grain size analysis *of both types of foam glass beads tested in this study. Grain size sieving test was carried out at the Institute of Geosciences of the FSU Jena in 2015.*

Sieve size [µm]	Weight retained [g]	Percentage retained [%]	Cumulative percentage passing [%]
Foam glass beads 0.1-0.3 mm			
>400	0.00	0.00	100.00
>315	0.41	0.43	99.57
>250	18.62	19.62	79.94
>200	27.38	28.86	51.09
>160	24.50	25.82	25.26
>125	14.23	15.00	10.27
>100	6.92	7.29	2.97
>80	0.00	0.00	2.97
>63	1.23	1.30	1.68
0	1.59	1.68	0.00
Foam glass beads 0.25-0.5 mm			
>800	0.00	0.00	100.00
>630	1.41	1.68	98.32
>400	41.17	48.98	49.34
>315	27.66	32.91	16.43
>250	12.31	14.65	1.78
>200	1.26	1.50	0.29
>160	0.00	0.00	0.29
>125	0.02	0.21	0.07
>100	0.06	0.07	0.00
>80	0.00	0.00	0.00

2.2. 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).

2.2.1. 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 sieving (sieves specified in Table 2) from 30 cm height into a shear cell of type No. 1. Normal force, shear force, shear velocity and lid displacement are measured at 5000 Hz and then down sampled to 5 Hz. Laboratory conditions are air conditioned during all the measurements (temperature: 23°C, humidity: 45%).

2.2.2. RST (Ring-shear test) procedure

In a RST a shear velocity of v = 30 mm min^{-1} is imposed. 18 measurements are done at normal stresses of σ_N = 500, 1000, 2000, 4000, 8000, and 16000 Pa (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.

2.2.3. VST (Velocity stepping test) procedure

To determine the dependence of the friction on the shear velocity v, a VST is performed. In this a shear velocity of v = 30 mm min^{-1} and a normal stress of σ_N = 2000 Pa are imposed. After reaching the plateau of the dynamic friction the measurement is started. Velocity is systematically decreased in logarithmic steps (Table 3).

Table 2: Sample overview *(GFZ = German Research Centre for Geosciences in Potsdam)*

GFZ-ID	Material	Sieve-ID	Sieving rate [g min^{-1} cm^{-2}]	File name
392-01	Foam glass beads 0.25-0.5 mm	GeoMod	4.5	392-01_GFZ_foamglass250_..., 413-01_GFZ_foamglass250_vst
393-01	Foam glass beads 0.1-0.3 mm	GeoMod	8.8	393-01_GFZ_foamglass100_..., 412-01_GFZ_foamglass100_vst
411-01	Foam glass beads 0.1-0.3 mm : quartz sand 0.1-0.4 mm (1:3)	GeoMod	17.1	411-01_GFZ_foamglass100-quartzsand_..., 411-01_GFZ_foamglass100-quartzsand_vst

Table 3: *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

2.3. Analysis method

2.3.1. RST analysis: Friction coefficients and cohesion

From the resulting shear stress curves (see e.g. Figure 2) three characteristic values (strengths) have been picked manually:

(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 3). 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 4). 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.

2.3.2. VST analysis: Rate-dependencies of dynamic friction

From the time-series data shear stresses τ are plotted as a function of log(shear velocity v) (Figure 5). The slope of a linear regression through the data approximates the dependency of the dynamic friction on the shear velocity v (rate-dependency).

2.3.3. Python-based analysis and visualization

Python scripts are provided along with this data set allowing analysis and visualization of the data. Python is an open-source, interpreted programming language. A complete Python-distribution is, for instance, provided by the “Anaconda”-platform, which can be downloaded from: https://www.anaconda.com/download/.

For conducting the RST and VST analyses, the “RSTanalysis.py”-and “VSTanalysis.py” files have to be opened and executed, respectively, in the “Spyder”-editor (Note: make sure that folders “Data files” and “Script” are stored in the same directory.)

3. File description

For each sample there exist the following files in the folder “2019-002_Warsitzka-et-al_Data files”:

- (i) RST shear curve data (“File name_ts.txt”; example Table 4)
- (ii) RST shear curve plot (“Filename_ts.pdf”; example Figure 2)
- (iii) RST friction data (“File name_peak.txt”, “File name_dynamic.txt”, “File name_reactivation.txt”; example Table 5)
- (iv) RST friction plot (“File name_linregr.pdf”; example Figure 3)
- (v) RST histograms of friction data (“File name_hist.pdf”; example Figure 4)
- (vi) VST data (“File name_vst.txt”; example Table 6)
- (vii) VST plot (“File name_vst.pdf”; example Figure 5)

Furthermore, Python-script files “RSTanalysis.py”-and “VSTanalysis.py” can be found in the folder “2019-002_Warsitzka-et-al_Scripts”. An overview of all files of the data set is given in **2019-002_Warsitzka-et-al_List of Files.**

3.1. Shear curve data

Shear curve data are given as (i) time series (ts) data in .txt-format (“File name_ts.txt”) and visualized as (ii) shear stress τ versus shear displacement d plots (“Filename_ts.pdf”) (Figure 2).

Table 4: Example of shear curve time series data (411-01). *First line is header. First column is time (in s). Columns 2-19 are shear forces (in N) for corresponding normal stresses as specified in the header of the respective columns (6 stress levels from 500 to 16.000 Pa, three repetitions each stress level).*

Time [s]	Normal stress [Pa]: 500	1000	2000	…
0.0	0.7862054109573364	0.9441303014755249	1.284285306930542	…
0.2	…	…	…	…
…	…	…	…	…

3.2. Friction data

Friction data are given as (iii) data pairs (normal stress σ_N and shear strength τ^*; Table 5) for peak, dynamic and reactivation friction in txt format (“File name_peak.txt”, “File name_dynamic.txt”, “File name_reactivation.txt”). They are visualized by (iv) plotting into Mohr Space (normal stress σ_N vs. shear stress τ) including a linear regression (“File name_linregr.pdf”; Figure 3). The results of the regression analysis (see 2.3) are plotted in (v) histograms for friction coefficients μ and cohesions C (“File name_hist.pdf”; Figure 4).

Table 5: Example of friction data (411-01, 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]
500	383.98
1000	697.20
…	…

3.3. VST data

VST data is given as (vi) time series data in .txt-format ("File name_vst.txt"; Table 6). The VST-time series is visualized by (vii) plotting shear velocity v and dynamic friction (shear stress τ divided by normal stress σ_N) against the shear displacement d ("File name_vst.pdf"; Figure 5). Furthermore, dynamic friction is plotted against the shear velocity v including a logarithmic curve fit reflecting the rate dependency of dynamic friction.

Table 6: Example of VST data (411-01). *First line is header. First column is time (in s). Second column is shear velocity (in mm s^{-1}). Third and fourth columns contain normal and shear force (in N).*

Time [s]	Shear velocity [mm s^-1]	Normal force [N]	Shear force [N]
0.0	0.5000932216644287	47.904502868652344	16.628713607788086
0.2	…	…	…
…	…	…	…

4. 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 7. Peak friction coefficients μ_P of all tested materials range between 0.70 and 0.75, dynamic friction coefficients μ_D between 0.52 and 0.55 and reactivation friction coefficients μ_R between 0.60 and 0.62. Peak cohesions C_P of all materials are negative within the range of standard deviation according to the linear regression method 2. This means that the material is cohesionless. A minor rate-weakening of ~1% per ten-fold change in shear velocity v is evident.

Table 7: Summary of RST data *(GFZ = German Research Centre for Geosciences in Potsdam, v = shear velocity)*

Parameter	Symbol	Unit	Linear least-squares regression method		Mutual two-point regression method	
			Value	Standard deviation	Value	Standard deviation
392-01_GFZ_foamglass250						
Coefficient of peak friction	μ_P	-	0.730	0.004	0.708	0.032
Peak cohesion	C_P	Pa	-105.53	33.00	-77.31	132.31
Coefficient of dynamic friction	μ_D	-	0.528	0.001	0.531	0.008
Dynamic cohesion	C_D	Pa	27.44	7.80	23.79	32.08
Coefficient of reactivation friction	μ_R	-	0.601	0.001	0.605	0.009
Reactivation cohesion	C_R	Pa	38.70	8.75	33.81	32.10
Rate dependency	$\Delta\mu_D/\Delta logv$	-	-0.0078	0.00003	n.a.	n.a.
393-01_GFZ_foamglass100						
Coefficient of peak friction	μ_P	-	0.746	0.004	0.727	0.030
Peak cohesion	C_P	Pa	-94.64	26.67	-71.36	102.76
Coefficient of dynamic friction	μ_D	-	0.542	0.001	0.546	0.012
Dynamic cohesion	C_D	Pa	22.70	5.64	19.84	25.44
Coefficient of reactivation friction	μ_R	-	0.598	0.002	0.600	0.008
Reactivation cohesion	C_R	Pa	35.99	11.43	33.29	32.88
Rate dependency	$\Delta\mu_D/\Delta logv$	-	-0.0032	0.00003	n.a.	n.a.

Table 7: *continued.*

411-01_GFZ_foamglass100-quartzsand						
Coefficient of peak friction	μ_P	-	0.728	0.004	0.703	0.036
Peak cohesion	C_P	Pa	-65.08	31.48	-37.68	115.53
Coefficient of dynamic friction	μ_D	-	0.547	0.001	0.554	0.021
Dynamic cohesion	C_D	Pa	64.89	8.72	58.73	34.13
Coefficient of reactivation friction	μ_R	-	0.610	0.001	0.616	0.011
Reactivation cohesion	C_R	Pa	75.63	10.20	67.75	36.71
Rate dependency	$\Delta\mu_D/\Delta logv$	-	-0.0049	0.00002	n.a.	n.a.

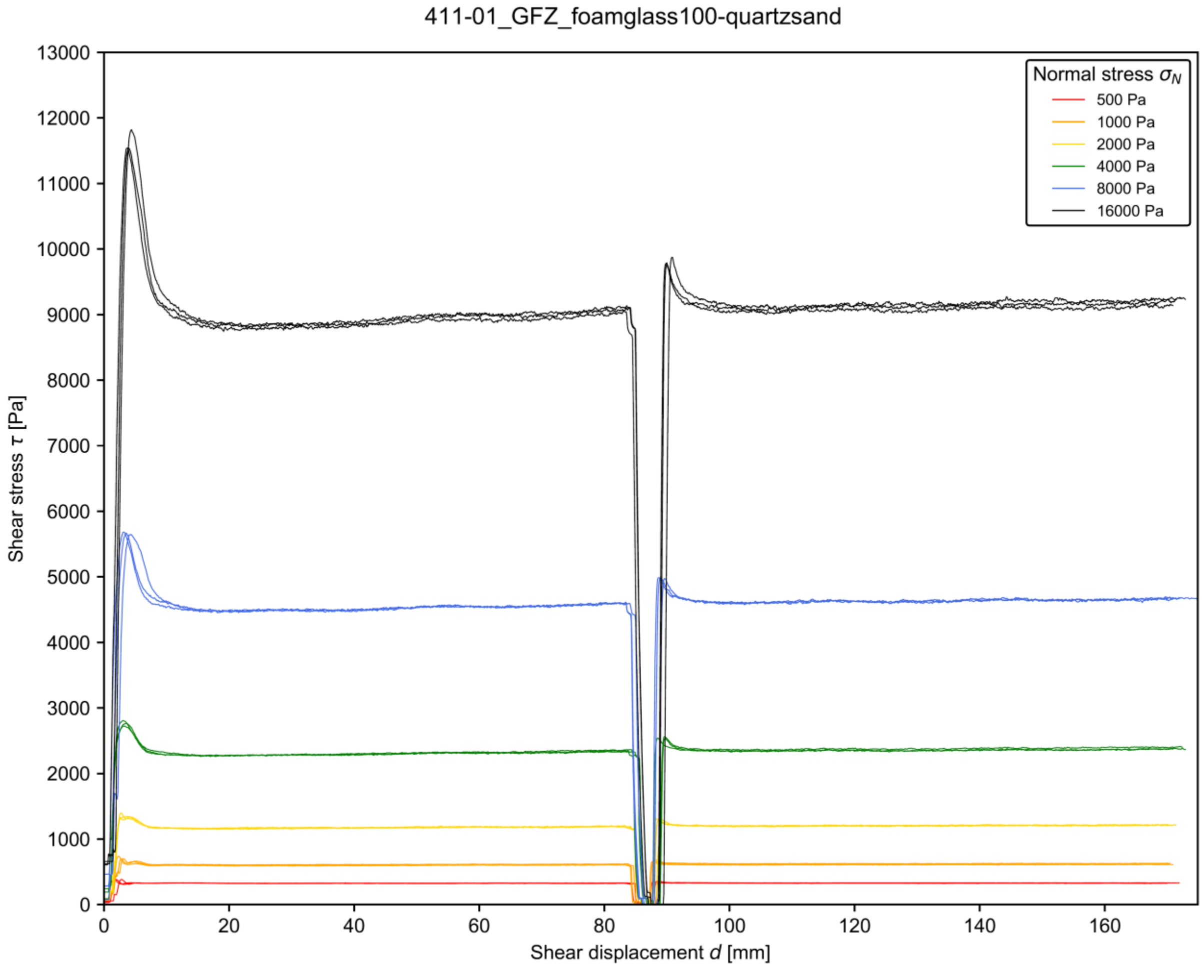

Figure 2: Example of shear curve plot (411-01). *Y-axis is shear stress τ, x-axis is shear displacement d. Each data set consists of 18 shear curves corresponding to 6 levels of normal stress* σ_N *with 3 repetitions each stress level.*

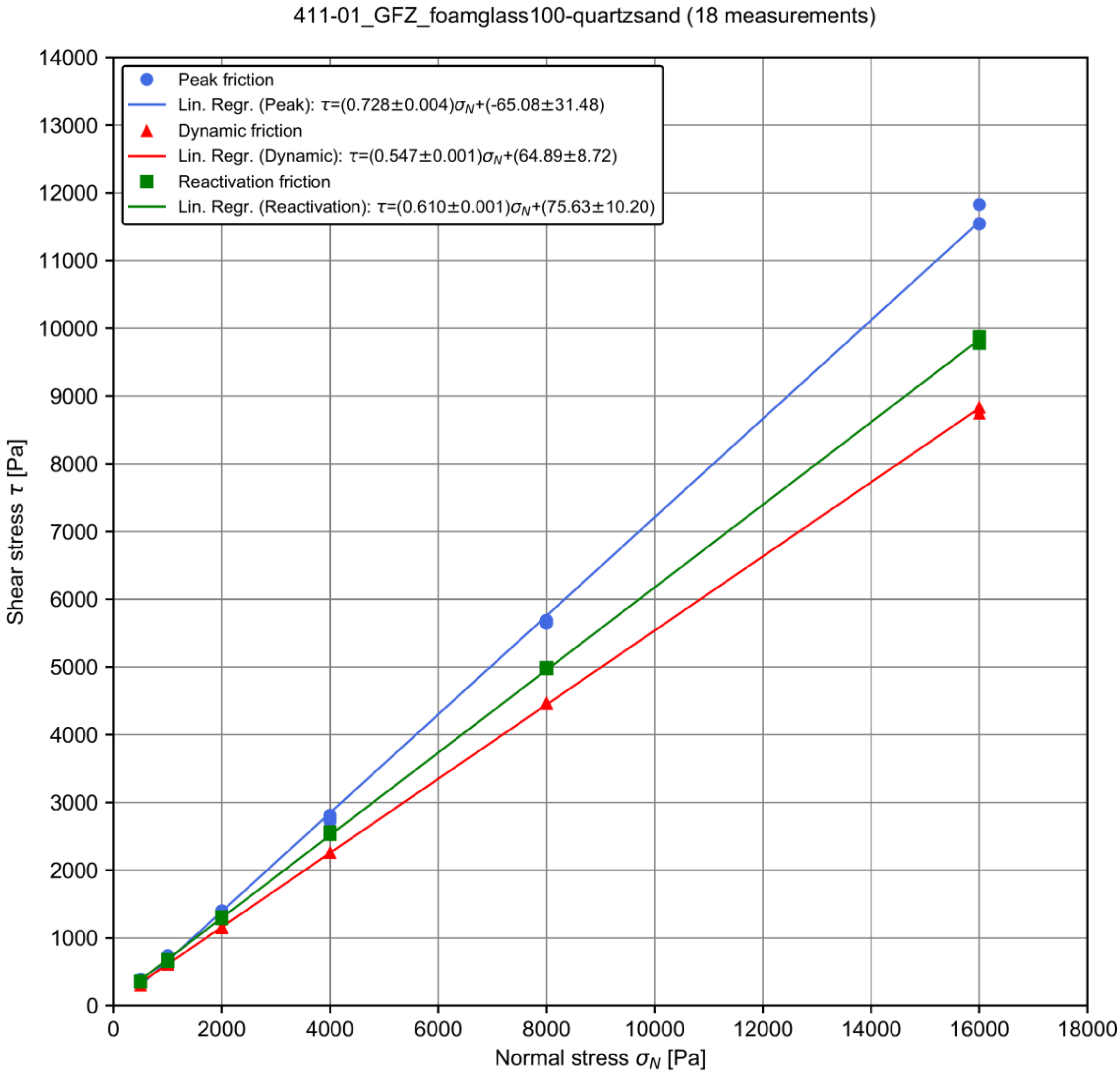

Figure 3: Example of friction plot (411-01). *Plot of all data pairs in the Mohr space (normal stress σ_N vs. shear stress τ) including curves of the corresponding linear least-squares regression.*

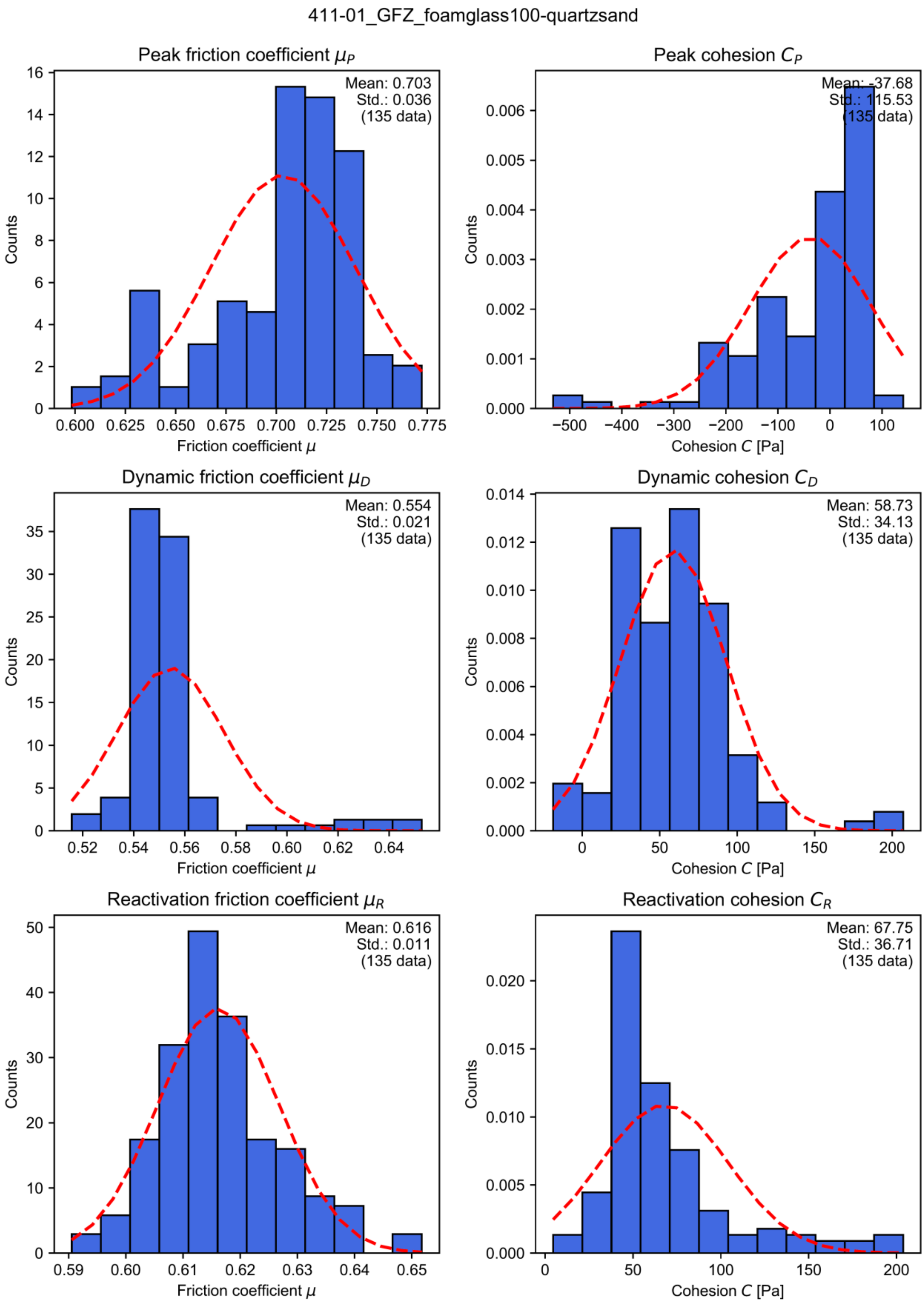

Figure 4: Example of histogram plot (411-01). *Histograms of mutual two-point regression results for slope (friction coefficient μ) and y-axis intercept (cohesion C). Red curves are synthetic normal distributions with the same mean and standard deviation (std.) as the data set for comparison.*

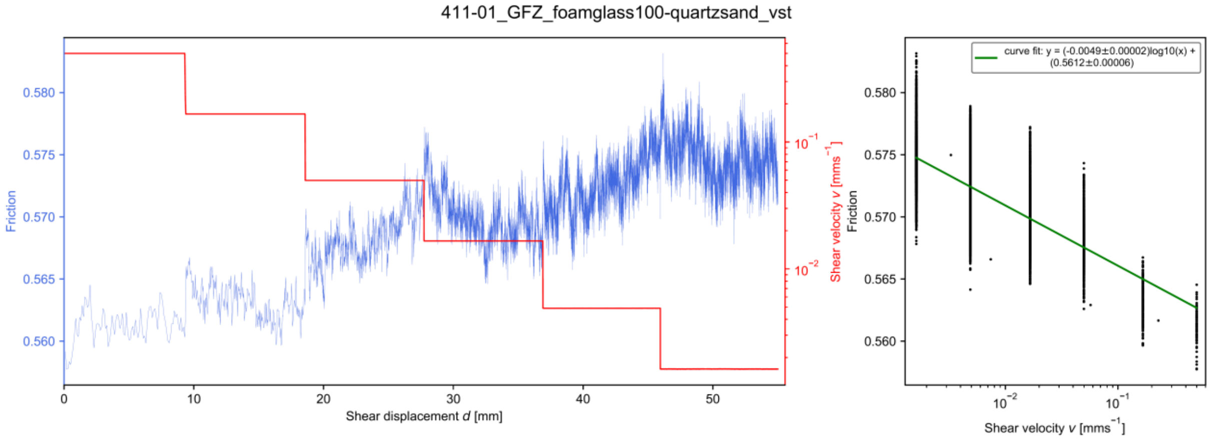

Figure 5: Example of the visualization of the VST data (411-01). *The shear velocity v is decreased stepwise (red curve), while the dynamic friction (shear stress τ/normal stress σ_N) is measured (blue curve). The logarithmic fit (green curve) reflects the slight decrease of the friction with increasing shear velocity v.*

5. References

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