Ring shear test data of glass beads 40-70 µm used for analogue experiments in the Helmholtz Laboratory for Tectonic Modelling (HelTec) at the GFZ German Research Centre for Geosciences in Potsdam

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1. Licence

2. Citation

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3. Table of contents

4. Data Description

This dataset provides friction data from ring-shear tests (RST) on glass beads used in the Helmholtz Laboratory for Tectonic Modelling (HelTec) at the GFZ German Research Centre for Geosciences in Potsdam as an analogue for “weak” brittle layers in the crust or lithosphere (Ritter et al., 2016; Santimano et al., 2015; Contardo et al., 2011; Reiter et al., 2011; Hoth et al., 2007, 2006; Kenkmann et al., 2007; Deng et al., 2018) or in stick-slip experiments (Rudolf et al., 2019a). The glass beads with a diameter of 40-70 μm have been characterized by means of internal friction coefficients μ and cohesions C as a remote service by the Helmholtz Laboratory for Tectonic Modelling (HelTec) at the GFZ German Research Centre for Geosciences in Potsdam.

According to our analysis the material shows a Mohr-Coulomb behaviour characterized by a linear failure envelope. Peak, dynamic and reactivation friction coefficients of the glass beads are μ_P = 0.46, μ_D = 0.40 and μ_R = 0.44, respectively. Cohesion ranges between 33 and 42 Pa. A rate-weakening of ~3 % per ten-fold change in shear velocity v is evident.

4.1. Materials tested

The tested material consists of glass beads with a grain size of 40-70 μm and a bulk density of 1500 – 1600 kg m^{-3}. The beads are produced using alkali-lime-glass and are sold as blasting medium in various grain size partitions by the company Kuhmichel Abrasiv GmbH (Germany; https://www.kuhmichel.com/en/products/glass-beads/). The grains of the material are near perfect spheres (Figure 1).

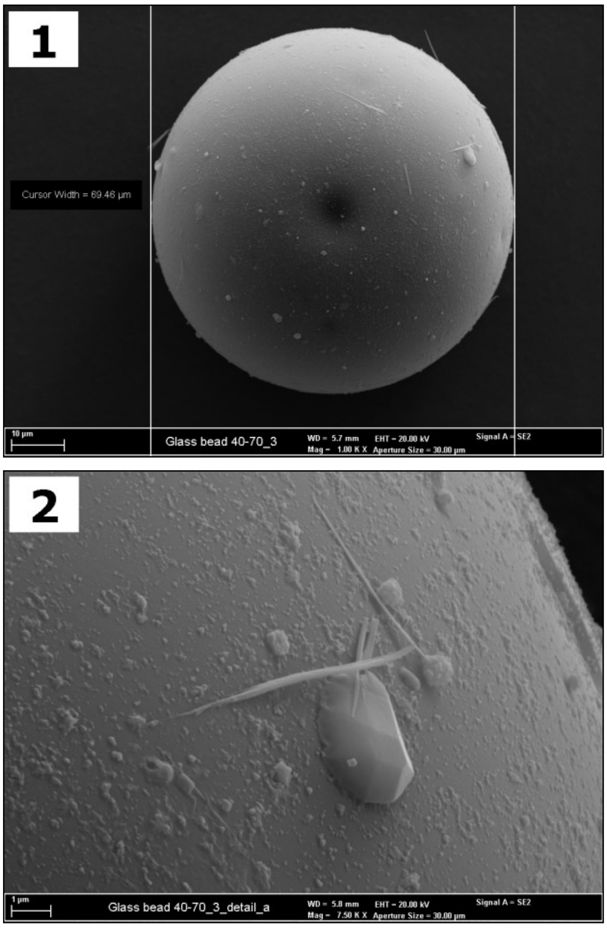

Figure 1: Examples of microscopic images *of the tested materials. (1) single glass bead 40-70 µm at 1000x magnification, (2) surface of a glass bead at 7500x magnification.*

4.2. Measurement procedure

The data presented here are derived by ring shear testing (RST) 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-01 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 granular 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).

4.2.1. 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 (sieve ID GeoMod, see 3.2.2.) 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%).

The 40-70 µm glass beads were sampled with the GFZ-ID 416-01 (VST) and 442-01 (RST). They showed a bulk density of 1550 kg m^{-3} and a sieving rate of 29 g min^{-1} cm^{-2} (GeoMod sieve).

4.2.2. 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. 18 individual tests are done at normal stresses of σ_N = 500, 1000, 2000, 4000, 8000, and 16000 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.

4.2.3. 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 1). The velocity steps are applied after having reached the plateau of the dynamic friction.

Table 1: *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	00:03:20
1	00:10:00
0.3	00:33:20
0.1	01:40:00

4.3. Analysis method

4.3.1. 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 2):

(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.

4.3.2. VST analysis: Rate-dependencies of dynamic friction

From the VST time-series data shear stresses τ are plotted as a function of log(v) (Figure 5). 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).

4.3.3. Python-based analysis and visualization

The data is analyzed and visualized using the custom software RST-Evaluation v.0.2.2 (https://gitext.gfz-potsdam.de/analab-code/rst-evaluation/-/tags/0.2.2) (Rudolf et al., 2019b). 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 and in Warsitzka et al. (2019). The current version uses a user interface to provide a more straightforward interaction with the software and does not require that the files are stored in specific folders, which differs from the older version in Warsitzka et al. (2019). Nevertheless, the inner workings are the same and have been optimized for performance and stability.

5. File description

The following files exist in the folder "Data files":

(i) RST raw data ("ID_[f][date_time].tdms")
(ii) RST shear curve data ("ID_ts.txt"; example Table 2)
(iii) RST shear curve plot ("ID_ts.pdf"; example Figure 2)
(iv) RST friction data ("ID_peak.txt", "ID_dynamic.txt", "ID_reactivation.txt"; example Table 3)
(v) RST friction plot and linear least-squares method data ("ID_linregr.pdf", "ID_fricstd.txt"; example Figure 3)
(vi) RST histograms of friction data and mutual linear regression data ("ID_hist.pdf", "ID_fricmut.txt"; example Figure 4)
(vii) VST raw data ("ID_VST.tdms")
(viii) VST plot ("ID_vst.pdf"; example Figure 5)

Furthermore, scanning electron mircoscope images of the glass beads can be found in the folder "SEM images". An overview of all files of the data set is given in the **List of Files.**

5.1. 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 ("ID_ts.txt") and visualized as (iii) shear stress τ versus shear displacement d plots ("ID_ts.pdf") (Figure 2).

Table 2: Example of shear curve time series data (442-01). *First line is header. First column is time (in s). Columns 2-19 are measured 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	46.98	81.60	88.11	…
0.2	…	…	…	…
…	…	…	…	…

5.2. RST friction data and analysis

RST friction data are given as (iv) data pairs (normal stress σ_N and shear strength τ^*; Table 3) for peak, dynamic and reactivation friction in .txt-format ("ID_peak.txt", "ID_dynamic.txt", "ID_reactivation.txt"). They are visualized by (v) plotting into Mohr Space (normal stress σ_N vs. shear stress τ) including a linear regression ("ID_linregr.pdf"; Figure 3), while the data is additionally given in .txt-format ("ID _fricstd.txt"). The results of the regression analysis (see 2.3) are plotted in (vi) histograms for friction coefficients μ and cohesions C ("ID_hist.pdf"; Figure 4), with the data additionally given in .txt-format ("ID _fricmut.txt").

Table 3: Example of friction data (442-01, 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]
500.00	267.34
1000.00	503.25
…	…

5.3. VST data and analysis

VST raw data (vi) are visualized (vii) by plotting shear velocity *v* and dynamic friction (simplified as shear stress τ divided by normal stress σ_N, i.e. no cohesion) against the shear displacement *d* ("ID_vst.pdf"; Figure 5). For analysis, 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. An example of the structure of VST data is given in Table 4.

Table 4: Example of VST data. *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	0.5000909566879272	47.85295104980469	18.14511489868164
0.2	…	…	…
…	…	…	…

6. Results

Our analysis reveals that the tested materials show a Mohr-Coulomb behaviour characterized by a linear failure envelope. Values of friction coefficients and cohesions are listed in Table 5. Peak, dynamic and reactivation friction coefficients of the glass beads stand as μ_P = 0.46, μ_D = 0.40 and μ_R = 0.44. Cohesion ranges between 33 and 41 Pa. Minor rate-weakening of ~3 % per ten-fold change in shear velocity *v* is evident (Figure 5).

Table 5: Summary of RST data *(v = shear velocity = 30 mm min^{-1})*

Parameter	Symbol	Unit	Linear least-squares regression method		Mutual two-point regression method	
			Value	Standard deviation	Value	Standard deviation
442-01_Glassbeads_40_70						
Coefficient of peak friction	μ_P	-	0.460	0.002	0.460	0.008
Peak cohesion	C_P	Pa	32.48	12.44	32.82	28.91
Coefficient of dynamic friction	μ_D	-	0.397	0.001	0.400	0.005
Dynamic cohesion	C_D	Pa	41.65	6.52	38.16	26.03
Coefficient of reactivation friction	μ_R	-	0.437	0.001	0.438	0.005
Reactivation cohesion	C_R	Pa	37.90	4.37	36.91	14.51
Rate dependency	$\Delta\mu_D/\Delta log v$	-	-0.0032	0.00002	n.a.	n.a.

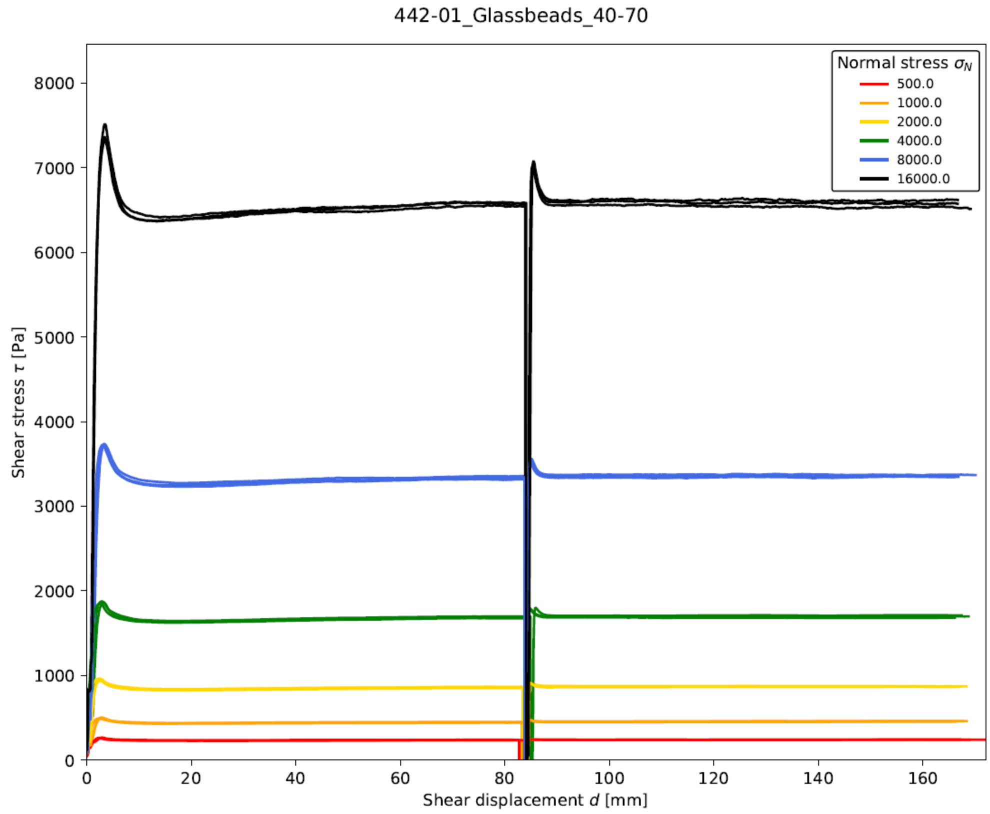

Figure 2: Example of shear curve plot (442-01). *Y-axis is shear stress τ, x-axis is shear displacement d. Each data set consists of 18 shear curves corresponding to 6 levels of normal stress σ_N with 3 repetitions each stress level (v = shear velocity = 30 mm min*$^{-1}$*).*

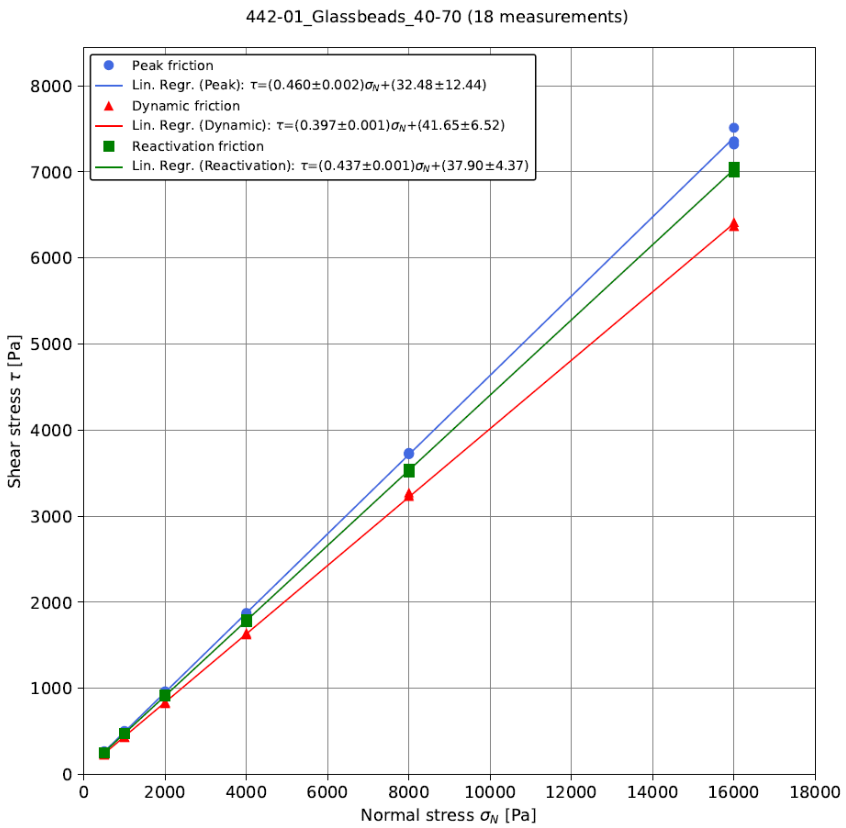

Figure 3: Example of friction plot (442-01). *Plot of all data pairs in the Mohr space (normal stress σ_N vs. shear stress τ) including curves of the corresponding linear least-squares (v = shear velocity = 30 mm min*$^{-1}$*).*

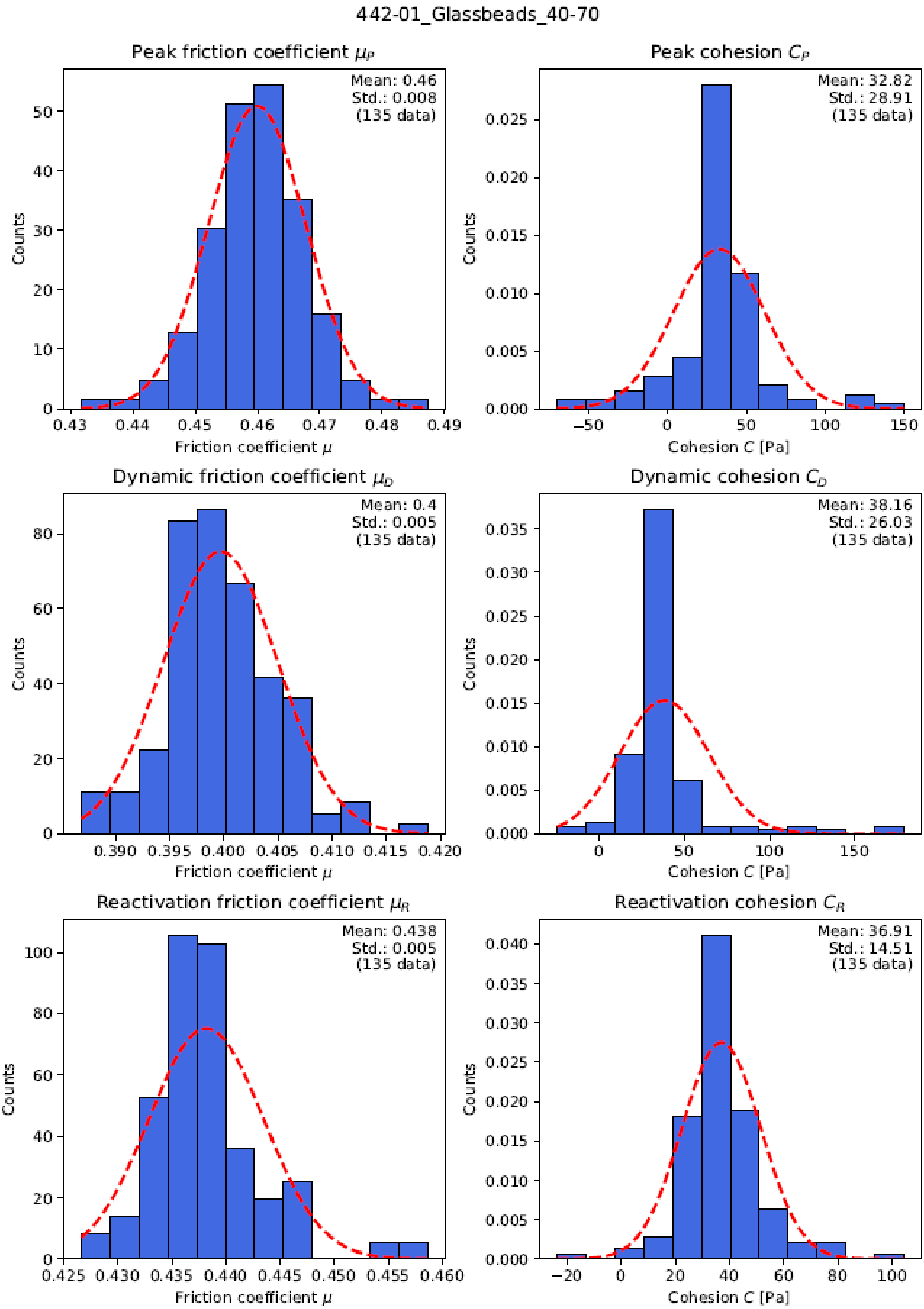

Figure 4: Example of histogram plot (442-01). *Histograms of mutual two-point regression results for slope (friction coefficient μ) and y-axis intercept (cohesion C). Red curves are synthetic normal distributions with the same mean and standard deviation (std.) as the data set for comparison (v = shear velocity = 30 mm min*$^{-1}$*).*

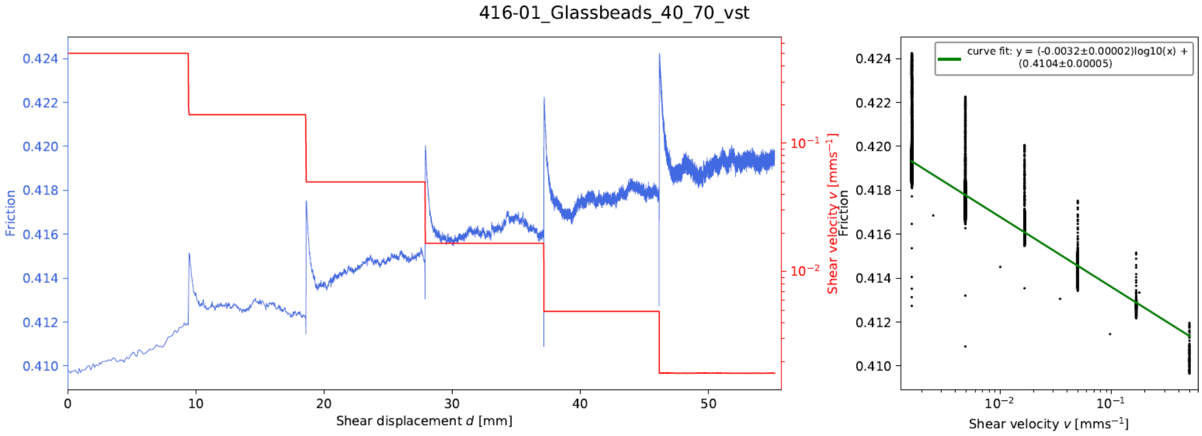

Figure 5: Example of the visualization of the VST data (419-01). *The shear velocity v is decreased stepwise (red curve), while the dynamic friction (shear stress τ/normal stress σ_N) is measured (blue curve). The logarithmic fit (green curve) reflects the slight decrease of the friction with increasing shear velocity v.*

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