falling within the 0.4-0.7 mm, and 0.25-0.4 mm fractions. Two sets of glass bead, i.e., the DB2017-B1 and B2 have a less homogeneous grain size distribution, with about 50% of the grains falling within the 0.35-0.6 mm, and 0.3-0.5 mm fractions. The two sets of quartz sand show consistence between the bulk density and grain size. Samples with the larger grains have higher densities, but the glass beads are not in this situation.

There is no distinct difference in grain sorting between the quartz and glass beads sand. The grain sorting of all materials varies from moderately to well sorted. Furthermore, we quantified the shape of grains using SEM photographic images following the methods of Klinkmuller et al. (*2016*). Grain shape and outline were measured and averaged from more than 60 grains of each material. The aspect ratio of four sets of materials varies from 1.34 to 1.56, of which two sets of quartz sand are characteristics with 1.54 and 1.56, respectively, and two sets glass bead are 1.34 and 1.36, indicating better grain shape of the latter, as well as of their textures.

2.3 Mechanical behaviour of materials

The mechanical properties of the friction materials were determined using Schulze ring-shear tester at the GFZ in Potsdam, at low confining pressures (0.1-10 kPa) and low shear velocities, similar to those observed in analogue experiments (*Lohrmann et al., 2003; Klinkmuller et al., 2016*). The tester consists of a shear cell containing the frictional materials and a lid, the latter is pressed on the material at given normal load that is constant throughout an experiment. There are sensors at the lid recording the torque, which can be transformed into shear stress. Ring-shear measurements are performed at a shear velocity of 3 mm/min for 4 min at a given normal load.

The shear stresses of four sets of materials are shown in *Fig.2*, indicating of varied frictional properties. At the onset of deformation shear stress increases quickly from zero to a peak level within a few millimetres of shear (strain hardening phase), and then drops to a stable value (strain softening phase) that retains for the rest of the deformation until to formation of a shear zone (sliding phase). When deformation is stopped, the sample unloaded and subsequently deformation is resumed. Renewed shearing results in a second and similar shear curve, resulting in another stress peak (reactivation phase). That is distinctly smaller than the first peak level, and roughly larger than the value of the first stable phase (*Fig.2*). It should be noted that the slightly increased values are artifact of the setup, result of the fact that the lid of shear cell slowly burrows into the tested materials during shearing, thereby increasing the friction at its side walls (*Lohrmann et al., 2003*). Furthermore, three values of friction strengths, e.g., peak strength, dynamic strength and reactivation strength, are picked manually from these curves, for the applied normal load. For each material, the three values of friction strengths, e.g., peak strength, dynamic strength and reactivation strength, are determined for six different normal loads varying between 500 Pa and 16000 Pa. Each normal load step is repeated three times, resulting in a total of 18 measurements for each material.

Measured values of peak strength, dynamic strength and reactivation strength are plotted against the applied normal stresses, respectively (*Fig.3*). All four sets of materials show an approximately linear increase of all three values with normal stresses, consistent with a Mohr-Coulomb failure criterion. Thus, a linear regression analysis is applied to the three values of all materials, to obtain their friction coefficient (u), which corresponds to the slope of the line and the friction angle ($\tan^{-1} u$). Furthermore, the cohesion (C) is the linearly extrapolated value at zero normal stress (*Table 1*). It should be noted that the failure envelopes for frictional materials is usually non-linear at low normal stresses. We use further an alternative method to derive friction coefficients and related cohesion of four sets of materials. This method calculates two point slopes and their intercepts for mutually combined pairs of a data set (e.g., *Klinkmuller et al., 2016*). A total of 18 measurements for each material thus resulted into 135 data sets for friction coefficient and cohesion. Those are then evaluated by means of calculating mean and standard deviation and comparing the probability density function to a normal distribution (*Fig.3*).

For the data sets obtained by two methods of the linear regression and mutual pairs regression analysis, we have found a slight difference between them. (1) peaks of the experimental probability density function are close to or narrower than a normal distribution. (2) cohesion values from the mutual pairs regression analysis are usually smaller than the values from the linear regression analysis. We thus prefer the calculated standard deviation as a conservative value for the four sets of frictional materials (*Table 1*).

For all the four sets of material, there is a systematic decrease in the values of friction coefficient from internal peak friction to internal reactivation friction, to internal dynamic friction (*Fig.3*). At the same way, the angles of them systematically decrease with 2-5 ° by turn (*Table 1*). Internal peak friction angles are 38 ° for two sets of quartz sand, with friction coefficients of 0.783 and 0.798 (e.g., DB2017-X1 and X2), respectively. Glass beads have much lower angles of internal peak friction of 31 °, and friction coefficients of 0.594 and 0.612 (e.g., DB2017-B1 and B2).

Internal reactivation friction and dynamic friction angles for sample DB2017-X1 are 34 ° and 31 °, with friction coefficients of 0.687 and 0.599, respectively. For sample DB2017-X2 with much smaller grain size than the former one, those angles are 33 ° and 30 ° with related friction coefficients of 0.656 and 0.582, indicating much smaller values than those of DB2017-X1. Two sets of glass beads have lower angles of internal reactivation friction and dynamic friction with 28 ° and 25 °, 30 ° and 26 °, respectively. Whilst the friction coefficients are 0.530 and 0.495, 0.569 and 0.493 for samples of

DB2017-B1 and B2. For the two sets of glass beads, the internal friction angles distinctly increase with the decreased mean grain size, but not in the quartz sands. It should be noted that the internal friction angles of glass beads are substantially smaller than that of quartz sands, no matter of their mean grain size.

The extrapolated cohesion values of internal peak friction, reactivation friction and dynamic friction vary considerably, in particular the internal peak friction. Sample DB2017-X1 is characterized by roughly similar cohesion values of reactivation friction and dynamic friction, e.g., 68 Pa, significantly larger than that of internal peak friction with -9 Pa. For sample DB2017-X2, the cohesion values of internal reactivation friction and dynamic friction are 125 Pa and 92 Pa, in contrast to peak 2 Pa of cohesion values at internal peak friction. Extrapolated cohesion values of glass beads are distinctly smaller than that of poor quartz sand (*Fig.3*). The cohesion values of internal reactivation friction and dynamic friction are 28 Pa and 16 Pa, 71 Pa and 37 Pa (e.g., DB2017-B1 and DB2017-B2), respectively. In the four sets of materials, the cohesion value of reactivation friction is highest, whilst the peak friction is the lowest.

Klinkmuller et al. (2016) used the same ring-shear tester to determine the material properties of frictional materials widely used in more than twenty laboratories worldwide. The obtained values correspond closely to ours, with internal friction angles of 32-40 °at peak friction, and mean values of 30-37 °, 28-34 °at reactivation friction and at dynamic friction, respectively. Most of their values of friction coefficient at dynamic friction and reactivation friction are roughly equal, and substantially smaller than that at peak friction.

3 Experiment setup and results

3.1 Experiment setup