The shear zone geometry of different granular analogue modelling materials under compression: insights from experiments monitored by X-ray Computed Tomography and image analysis software.

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We have chosen six different granular materials (Table 1) from the 2008 analogue material benchmark (Geomod 2008) to investigate shear zone formation (zones of dilatancy) under a compressional set-up observed with X-ray Computed Tomography (XRCT). The shear zone pattern was evaluated with image analysis software and compared with the physical properties of the granular material determined by tests for the material benchmark (Geomod Workshop 2008) performed at the Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences.

The sandbox (30 cm by 20 cm) has one movable sidewall, driven by a computer-controlled servomotor at 20 cm/h. A 12 cm wide and 20 cm long sheet of hard cardboard was placed on the base of the sandbox and attached to the moving sidewall creating a velocity discontinuity 12 cm in front of the moving wall. The sand-layer is 3 cm thick for each experiment. The whole sandbox was covered on the inside with Alkor foil to reduce sidewall friction. The set-up follows experiment 2 of the Geomod 2008 analogue-numerical modelling comparison.

In a first, short-deformation experiment, the sand volume was observed with XRCT scans in 3 mm increments of shortening from 0 mm to 15 mm. Each experiment was repeated three times to determine the variability of the shear zone geometry investigating all granular materials. In a second, long-deformation experiment, the sand volume was scanned at 2 mm increments of shortening from 0 mm to 10 mm shortening, followed by scans at 5 mm increments of shortening until 65 mm of maximum shortening had been achieved. The long-deformation experiments were repeated twice and two natural quartz sands had been investigated.

Four natural quartz sands, one batch of glassbeads and one batch of corundum sand have been investigated. The physical properties (Table 1 and Fig.1) of these six granular materials differ in grain size distribution, grain shape, bulk moduli and bulk density. Natural quartz sand from Stanford University, Helmholtz Center Potsdam – GFZ German Research Centre for Geosciences and glassbeads from the GFZ are round to very round in contrast to the sub-angular to angular quartz sands from University Bern, Institut Français du Pétrole (IFP) and the corundum sand from IFP. GFZ glassbeads, Bern quartz sand, IFP quartz sand and IFP corundum sand are fine-grained, whereas Stanford and GFZ quartz sands are medium-grained (Fig.1).

Comparing the short-deformation experiments large variations in shear zone angles are measured between sub-rounded to rounded sands and sub-angular to angular sands. In general, rounded sands show steeper shear zone angles than angular sands. Comparison between each experiment with the same sand shows good reproducibility for all three sub-rounded to rounded sands and poor reproducibility for sub-angular to angular sands.

Shear zone angles have been calculated (Fig.2) using Mohr-Coulomb criterion with failure planes making an angle (α) with the direction of the major principal stress:

$$\alpha = 45° - \frac{\varphi}{2},$$

with φ the angle of internal friction. The results show differences between measured and calculated shear zone angles specifically for sub-angular to angular sands (Fig.2).

Differences between angular and rounded sand are confirmed by results of long-deformation experiments using Bern quartz sand and GFZ quartz sand. The rounded GFZ quartz sand shows very good reproducibility and steeper shear zones than Bern quartz sand. Furthermore, Bern quartz sand shows large variations in shear zone spacing and number of shear zones.

Granular Material	Peak internal friction (°)	Dynamic internal friction (°)	Peak basal friction (°)	Dynamic basal friction (°)	Mean grain size (µm)	Bulk Modulus (MPa) ±10%	Bulk Density (g/cm^3)	Grain shape PARIS/ SH1
GFZ Quartz Sand	34.2±1.1	29.7±0.6	22.3±0.6	17.7±0.6	301	1054	1.7	1.4 1.21
IFP Quartz Sand	36.9±0.6	31.8±0.6	18.3±1.1	14.0±1.1	127	925	1.4	3.4 1.31
Stanford Quartz Sand	33.0±1.1	30.1±0.6	20.8±0.6	16.2±0.6	271	1257	1.7	0.9 1.15
Bern Quartz Sand	36.9±0.6*	30.8±1.0*	17.5±3.3*	15.6±2.4*	171	962	1.5	2.7 1.30
IFP Corundum Sand	34.6±0.6	31.4±0.6	26.1±0.6	24.7±0.6	124	1545	2.1	6.3 1.53
GFZ Glass-beads	25.6±0.6	21.8±0.6	15.1±0.6	14.0±0.6	174	1084	1.5	1.7 1.10

Tab.1: Physical Properties of tested granular materials. Basal friction determined using Alkor foil. All friction values are the mean of three ring-shear test cycles, except Bern quartz sand (*) with a mean out of 9 test cycles. Bulk modulus has an error of ± 10%. Bulk density calculated for undeformed granular material. PARIS shape factor describes convexity and concavity (0 => only convexity). SH1 compares grain shape with a circle (1.0 => circle).

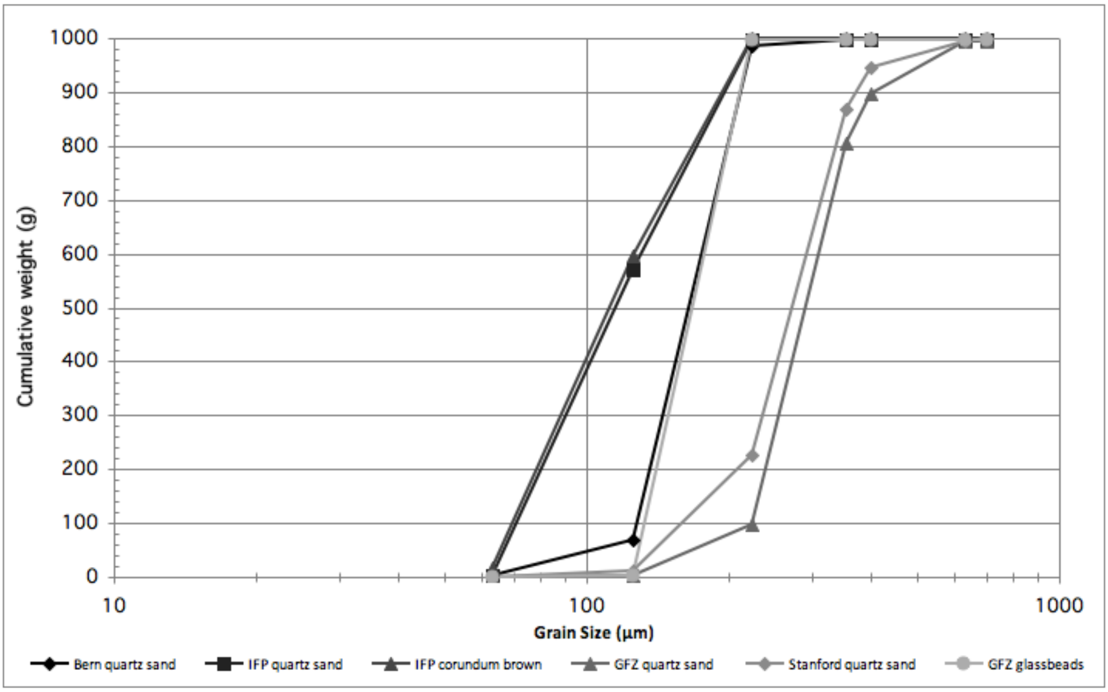

Fig.1: Sieving analysis cumulative weight curve for the used analogue modelling granular materials.

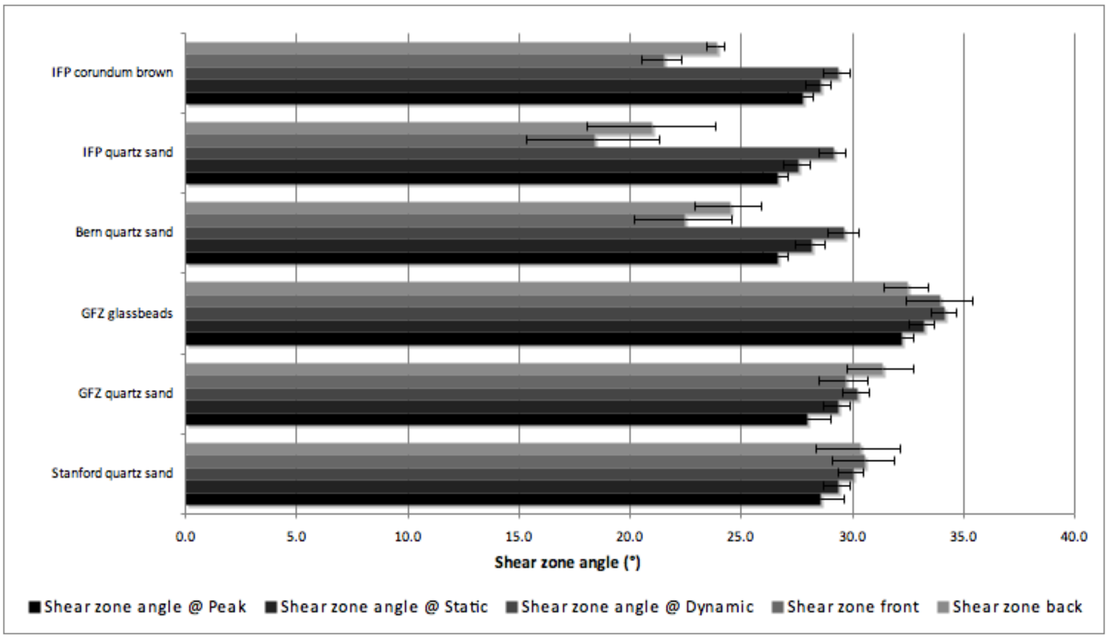

Fig.2: Shear zone angles measured compared to calculated shear zone angles (see formula above). Sub-angular to angular grains are IFP Corundum brown, IFP quartz sand, and Bern quartz sand. Sub-rounded to rounded grains are GFZ glassbeads, GFZ quartz sand, and Stanford quartz sand.