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Properties of granular analogue model materials: A community wide survey

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ABSTRACT

We report the material properties of 26 granular analogue materials used in 14 analogue modelling laboratories. We determined physical characteristics such as bulk density, grain size distribution, and grain shape, and performed ring shear tests to determine friction angles and cohesion, and uniaxial compression tests to evaluate the compaction behaviour. Mean grain size of the materials varied between c. 100 and 400 μm. Analysis of grain shape factors shows that the four different classes of granular materials (14 quartz sands, 5 dyed quartz sands, 4 heavy mineral sands and 3 size fractions of glass beads) can be broadly divided into two groups consisting of 12 angular and 14 rounded materials. Grain shape has an influence on friction angles, with most angular materials having higher internal friction angles (between c. 35° and 40°) than rounded materials, whereas well-rounded glass beads have the lowest internal friction angles (between c. 25° and 30°). We interpret this as an effect of intergranular sliding versus rolling. Most angular materials have also higher basal friction angles (tested for a specific foil) than more rounded materials, suggesting that angular grains scratch and wear the foil. Most materials have an internal cohesion in the order of 20–100 Pa except for well-rounded glass beads, which show a trend towards a quasi-cohesionless ($C < 20$ Pa) Coulomb-type material. The uniaxial confined compression tests reveal that rounded grains generally show less compaction than angular grains. We interpret this to be related to the initial packing density after sifting, which is higher for rounded grains than for angular grains. Ring-shear test data show that angular grains undergo a longer strain-hardening phase than more rounded materials. This might explain why analogue models consisting of angular grains accommodate deformation in a more distributed manner prior to strain localisation than models consisting of rounded grains.

1. Introduction

Experimental simulations of brittle deformation of the earth using scaled analogue models have evolved from a qualitative phenomenological approach towards a more quantitative analysis (Ranalli, 2001). Along with this evolution, the number of different granular materials used in analogue modelling experiments has increased (Mandl et al., 1977; Savage and Sayed, 1984; Krantz, 1991; Cobbold and Castro, 1999; Schellart, 2000; Lohrmann et al., 2003; Rossi and Storti, 2003; van Mechelen, 2004; Panien et al., 2006; Rosenau et al., 2009; Graveleau et al., 2011; Gomes, 2013). Granular materials are commonly used in analogue models for simulating upper crustal deformation. In direct comparisons of scaled analogue experiments to test the reproducibility of model results amongst different physical modelling laboratories, Schreurs et al. (2006, 2016) showed that differences in model materials induce variations in the geometry and evolution of structures. In order to evaluate to what extent the results of physical modelling in tectonics depend on the properties of the model materials and to allow for meaningful quantitative comparisons of model results, it is essential that the physical characteristics and the mechanical behaviour of the materials be determined in a consistent way.

Here, we present an analogue material comparison investigating the properties of dry granular materials from physical modelling laboratories worldwide. In this comparison 14 laboratories participated and a total of 26 granular model materials were analysed using standard methods and apparatuses. We determine the physical characteristics (e.g. density, grain size distribution, and grain shape) and perform ring-shear tests and uniaxial confined compression tests to characterise the mechanical behaviour of each of these materials. We then discuss the implications for comparability of the materials amongst themselves and their suitability for analogue modelling. All ring-shear and uniaxial confined compression tests were performed by the same person to assure as much as possible a repeatable material handling and filling procedure.

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Original data generated in the context of this benchmark have been published open access and are available in Klinkmüller et al. (2016a–d).

2. Materials

Participating laboratories sent 7 kg of granular material to the Helmholtz Centre Potsdam, German Research Centre for Geosciences (GFZ), where all material tests have been performed. The materials were stored prior to testing for at least 1 month to acclimatise to the air-conditioned laboratory environment at GFZ. During the measurement periods laboratory temperature and air humidity were 23 ± 2 °C and 45 ± 5%, respectively. Each of the tested materials has been assigned an abbreviation with the first three capital letters identifying the laboratory and the last three capital letters designating the type of material.

The granular materials comprise both natural and artificial materials (Table 1; Fig. 1). Natural materials include quartz sands and heavy mineral sands (garnet and zircon sands). Most natural materials are shock heated to eliminate the clay fraction and are sieved to specific grain size distributions by the suppliers. STUSAN and GFZSAN are mixtures of pure quartz sand and a few percent of dyed quartz sand. These “salt'n'pepper” mixtures provide a visual texture that allows monitoring of analogue model deformation using optical correlation techniques (e.g. Adam et al., 2005, 2013). ULISAN is a 1:1 mixture of quartz sand and dyed quartz sand. Artificial materials include corundum sands and glass beads. Brown and white corundum sands consist of aluminium oxides and are produced from reduced melt of high-quality bauxite and pure, mineralised clay, respectively. The glass beads are high-quality vaporised glass spheres. The 26 tested granular materials comprise 14 quartz sands, 5 dyed quartz sands, 4 heavy mineral sands and 3 types of glass beads with different grain size fractions. To distinguish dyed from non-dyed quartz sands, we added “col” (for “coloured”) to the six-letter abbreviation designating the dyed materials.

3. Bulk density, grain size and grain shape

3.1. Density measurements

3.1.1. Measurement method

The bulk density of each granular material was estimated by measuring the mass of a known volume. The material was sifted from a height of 30 cm at a filling rate of c. 250 ml/min into the shear cell of a ring-shear tester (see next section) with known volume. Sifting was done using a sieve structure identical to the one described by Schreurs et al. (2016). Excess material was scraped off to achieve a plane surface.

3.1.2. Results: Density

Bulk densities vary between 1.2 and 1.7 for all granular materials, except for the heavy mineral sands, which have densities between 1.8 and 2.8 g/cm^3 (Table 2).

3.2. Grain size and shape

3.2.1. Grain size analysis

Grain size analysis was performed with a sieve shaker Retsch AS 200 equipped with sieves of 200 mm diameter and six mesh sizes of 63 μm, 125 μm, 224 μm, 355 μm, 400 μm, and 630 μm, yielding five constrained and two unconstrained (<63 μm and >630 μm) grain size classes. Shaking time and amplitude were 4 h and 3 mm, respectively. Preliminary tests verified these conditions as being effective in separating the grains in typical sands. From an initial charge of 1 kg the maximum material loss was 5 g (i.e. 0.5 weight-%). The results of the sieve analysis are presented as grain size distribution curves, in which particle grain size is plotted against cumulative weight percentage (Fig. 2).

The original sieve data have been published open access and are available in Klinkmüller et al. (2016b).

Table 1
Overview of tested granular materials with details on origin, composition and supplier. First three capital letters in third column identify the participating institute: CAS = Czech Academy of Sciences, GFZ = German Research Centre for Geosciences, IFP = IFP Energies nouvelles, KYU = Kyoto University, NTU = National Taiwan University, RHU = Royal Holloway University, STU = Stanford University, TLW = TecLab Wroclaw, UBE = University of Bern, UCP = Université de Cergy Pontoise, ULI = Université Lille, UOP = Universidade Federal de Ouro Preto, UPA = Università degli studi di Parma, UPU = Uppsala University, and UTO = University of Toronto. Last three capital letters in third column identify the type of granular material: CSB = Corundum sand brown, CSW = Corundum sand white, GLB = Glass beads, GRS = Garnet sand, SAN = Quartz sand, and ZCS = Zircon sand.

Affiliation	Granular material	Abbreviation	Further details and/or origin	Composition (wt.%)	Supplier or reference
Czech Academy of Sciences	Quartz sand	CASSAN	Sklopísek, Poland	98.9% SiO_2	www.glassand.eu
Helmholtz-Zentrum Potsdam, GFZ	Glass beads	GFZGLB[a]	Artificial		www.worf.de
	Garnet sand	GFZGRS		$Fe_3Al_2(SiO_4)_3$	www.kominex.de
	Quartz sand	GFZSAN[b]	G23	95% SiO_2	Lothar Fischer
	Quartz sand (dyed)	GFZSAN col.	G12	95% SiO_2	id.
	Zircon sand	GFZZCS		$ZrSiO_4$	www.mineralmuehle.com
IFP Energies nouvelles	Corundum brown	IFPCSB	Artificial	99.8% Al_2O_3	www.mineralex.fr
	Corundum white	IFPCSW	Artificial	99.8% Al_2O_3	www.mineralex.fr
	Quartz sand	IFPSAN	Sifraco GA39	98% SiO_2	www.sibelco.fr
Kyoto University	Quartz sand	KYUSAN	Toyoura sand, Japan	93% SiO_2 4% Al_2O_3	www4.ocn.ne.jp/~toyoura/
National Taiwan University	Quartz sand	NTUSAN	Eolian sand	99.5% SiO_2	www.sibelcoasia.com
	Quartz sand (dyed)	NTUSAN col.			
Royal Holloway University	Quartz sand	RHUSAN	Lochaline sandstone	98.8% SiO_2	lochalinequartzsandltd.vpweb.co.uk
	Quartz sand (dyed)	RHUSAN col.			
Stanford University	Quartz sand	STUSAN[b]	Ordovician sandstone (Ottawa, Illinois)	Not known	www.agsco.com
Technical University Wroclaw	Quartz sand	TLWSAN	Osiecznica deposit, Poland	98.9% SiO_2	
University of Bern	Quartz sand	UBESAN	Buntsandstein, Schnaittenbach, Germany	99% SiO_2	www.carloag.ch
Université de Cergy Pontoise	Quartz sand	UCPSAN	Sifraco VC32	98.7% SiO_2	www.sibelco.fr
Université Lille	Quartz sand	ULISAN	Sifraco NE34	99.7% SiO_2	www.sibelco.fr
		ULISAN col.[c]			
Universidade Federal de Ouro Preto	Quartz sand	UOPSAN	Itacolomi Group metasandstone, Brasil	Not known	
	Quartz sand (dyed)	UOPSAN col.			
Università degli studi di Parma	Quartz sand	UPASAN		99.8% SiO_2	www.valligranulati.it
Uppsala University	Quartz sand	UPUSAN		99% SiO_2	

[a] Three different grain size fractions.
[b] Contains a few percent of dyed quartz sand.
[c] 1:1 mixture of quartz sand and dyed quartz sand.