Journal of Structural Geology 46 (2013) 158–166

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

# Investigating new materials in the context of analog-physical models

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ARTICLE INFO

*Article history:*
Received 7 February 2012
Received in revised form
19 September 2012
Accepted 20 September 2012
Available online 5 October 2012

*Keywords:*
Analog modeling
Sand mixtures
Angle of internal friction
Shear strength
Rheology

ABSTRACT

To broaden the availability of granular materials that are suitable for the analog modeling of upper crustal deformation, we investigated the mechanical behaviors of pure quartz sand and two sand mixtures (quartz sand–powdered barite and quartz sand mica crystals) using ring-shear tests and simple convergent sandbox experiments. The ring-shear test results indicate that the three materials have similar peak friction angles (between 39.25° and 36.02°), but the magnitude of the shear strain and the shear strength required to cause their failure are different. The differences between the analog models are identified by distinct fault kinematics and different grain flows, which are primarily related to differences in the plastic elasto-frictional rheology. We conclude that the use of the quartz–mica mixture, which showed the strongest distributed (plastic) deformation, can improve analog models where different materials are required to simulate crystalline basement (sand) and supracrustal rocks (sand mica mixture). This is a common situation in extension and inversion tectonics, such as, for example, in inversion tectonics, when a granitic basement block acts as a buttress.

## 1. Introduction

The materials that are most frequently used for the physical modeling of brittle deformation are dry quartz sand and wet clay. The frictional behavior of these materials is similar, but the cohesive strength of sand is much less (but not negligible) than that of wet clay (Withjack et al., 2007). Several studies concerning the mechanical properties of dry sand and wet clay have been published (e.g., Mandl, 1988; Krantz, 1991; Schellart, 2000; Eisenstadt and Sims, 2005; Withjack and Schlische, 2006; Panien et al., 2006). These studies suggest that the frictional characteristics of sand and clay in a normal gravity field obey the Coulomb Failure Criterion (Byerlee, 1978):

$$\tau = C_0 + \mu\sigma_N \tag{1}$$

where $\tau$ and $\sigma_N$ are, respectively, the shear and normal stresses, $C_0$ is the cohesive strength, and $\mu$ is the coefficient of internal friction.

Lohrmann et al. (2003) have shown that quartz sand is characterized by an elastic/frictional plastic behavior in which strain hardening precedes faulting, after which strain softening occurs until stable stress values are obtained. This behavior simulates that of brittle rocks. However, the use of dry sand and wet clay as analog materials to simulate the upper crust is an oversimplification, and it does not satisfy situations where the simulation of rock units with different rheological behaviors are called for. To address this problem, several researchers (e.g., Schellart, 2000; Schöpfer and Steyrer, 2001; Rossi and Storti, 2003; Panien et al., 2005) have investigated new, alternative analog materials. Schöpfer and Steyrer (2001) used different sand types (sifted natural dry quartz with a rough surface and low sphericity, the same quartz without clay mineral fractions and a coarser-grained industrially produced sand with smooth grain surfaces and high-sphericity) in strike-slip fault models, and they have shown that the geometry of shear zones does not change with the varying thickness of the sand pack but that it instead changes with grain properties. Gabrielsen and Clausen (2001) used plaster of Paris to enhance the delicate details of extensional tectonics. Lohrmann et al. (2003) described changes in the geometry, kinematics and dynamics of convergent sandbox experiments using sand with different grain-size distributions and different shear apparatus filling techniques. Rossi and Storti (2003) employed fine-grained, high-sphericity, low-density aluminum and siliceous hollow microspheres to simulate the mechanical behavior of ductile detachments within sand packs. They argued that an extremely fine-grained material provides more structural detail and better scaling than coarser-grained sand. Glass microbeads were utilized by several authors to simulate multilayered mechanical stratigraphy, weak sedimentary rocks or ductile shear zones (e.g., Turrini et al., 2001; Panien et al., 2006; Massoli et al., 2006; Yamada et al., 2006; Ravaglia et al., 2006; Yagupsky et al., 2008; Konstantinovskaya and Malavieille, 2011). This

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http://dx.doi.org/10.1016/j.jsg.2012.09.013

material consists of highly spherical grains that have an angle of internal friction consistently lower than that of quartz sand.

The aim of our work was to contribute to the study of new elastic and frictional plastic analog materials. Shortening experiments were conducted with three types of sands, the mechanical properties of which are characterized in detail. The study is not intended to represent any particular natural geological setting, but to provide an approach for the identification of materials suitable for differentiation among crystalline basement and supracrustal rocks in inversion tectonics or thick-skinned fold-and-thrust belts. Many sandbox experiments on basin inversion have been conducted to analyze hanging wall deformations using rigid footwalls (made of acrylic or wood) (e.g., McClay, 1989; Buchanan and McClay, 1992; Gomes et al., 2010). However, these rigid footwalls cannot deform as a basement rock might deform in nature. In addition, the high strength contrast between the rigid footwalls and the analog material influences the model results. We analyzed pure quartz sand and mixtures of sands with two products of differing composition and shape: sand with powdered barite (2:1 by weight) and sand with mica crystals (14:1 by weight).

First, we used a ring-shear tester to examine the optimal ratio between sand and barite and sand and mica crystals. In addition, we analyzed the relationship between the frictional properties of the quartz sand and two preparation techniques. Second, we measured the angle of the internal friction and the cohesion of the pure quartz sand (for ease of description, in the following, we refer to the pure quartz sand only as sand) and the sand mixtures. Third, we applied three analog models to each of the three model materials and compared the results. Finally, we used the model results to improve our knowledge of the mechanical behavior of granular materials.

It was not our intention to monitor the strain history of the sand mixture models, but rather to compare the mechanical response of each of them with that of the sand model. Accordingly to Richard and Krantz (1991) and Withjack et al. (2007), the primary deformation mechanism in sand is localized deformation (e.g., failure), although distributed deformation is also important (e.g., Rutter, 1986). Distributed deformation causes strain without loss of continuity, commonly referred to as ductile behavior. In the following text, we refer to the distributed deformation process in the vertical and in the horizontal directions (as described by the above authors) as vertical grain flow or vertical ejection of the sand and as horizontal grain flow, respectively. The latter is sometimes referred as layer-parallel shortening, as used by Koyi (1995).

## 2. The mechanical properties of sand and sand mixtures

### 2.1. Materials and methods

The Schulze ring-shear tester (RST-XS) was developed in 1994 based on equipment that has been used in soil mechanics (rotational shear testers) since the 1930s. Among the simple shear apparatuses that are currently available, the RST-XS is notable because it works with low normal loads that are within the range of stresses applied to the model materials in sandboxes.

In the present study, the methodology for use of the RST-XS followed that described by Ellis et al. (2004) and Panien et al. (2006). The measurements of the internal friction (and basal friction) angles and cohesion strength were performed with normal stresses, which ranged from 800 to 2400 Pa, in intervals of 400 Pa. The computer-controlled RST-XS recorded the shear stress in three different situations: at fault initiation (the peak strength), at fault reactivation (the second peak strength or the reactivation peak strength) and at fault sliding (the dynamic–stable strength); it was also used to generate stress–strain curves in diagrams of shear stress plotted as a function of time.

The values obtained by the RST-XS were used to produce a second diagram to compare the shear stress to the normal stress (Coulomb–Mohr diagram). The coefficient of the internal friction (and basal friction) was derived from the linear regression analysis of the diagram, whereas the cohesion was inferred by extrapolation along the straight Coulomb fracture envelope to its intersection with the shear stress axis.

In preliminary tests, we analyzed several ratios of sand mixtures to find a material that was characterized by a peak angle of internal friction similar to that of the sand. This was important because we were searching for materials that were only slightly different from sand (such as slightly less competent supracrustal rocks compared to infracrustal rocks). The tests revealed that the sand mixture ratios had no major influence on the peak angles of internal friction (for example, the sand mica mixtures of ratios 14:1 and 24:1, by weight, revealed a difference of only 2.03° in their peak angles of internal friction). Thus, the choice of the ratio (by weight) of our sand mixtures, sand with barite, 2:1, and sand with mica crystals, 14:1, has only impacted the shear strength and cohesion values.

Measurements of the frictional properties of sand were obtained under different preparation techniques following Krantz (1991), Schellart (2000) and Lohrmann et al. (2003). The annular cell of the ring-shear tester was filled by both sifting and pouring (and afterward, leveled by scraping), and different fill heights were examined. We analyzed the frictional properties obtained by pouring the analog material into the test cell, as pouring, in contrast to sifting, can prevent the loss of powdered barite during preparation. Moreover, to avoid any loss of the low-density mica crystals, especially during pouring, we poured this mixture directly from the edge of the annular cell (thus, the height was equal to zero). Finally, in one sample, a ≤210 μm grain size was analyzed.

To minimize measurement errors, each test was repeated three times, and a total of 15 tests were performed for each sample. The statistical calculations provided $R^2$ correlation values (the square of the correlation coefficient) that were greater than 0.99 for all tests.

### 2.2. Results

#### 2.2.1. Frictional properties of sand as a function of filling techniques

The experimental results presented in Table 1(a) reveal that the filling technique (sifting or pouring) is the only parameter that influences the angle of the internal friction of our sand. However, these variations occur only in the peak strength values, i.e., at failure (a localized shear zone). The peak friction (the internal friction angle ($\Phi$) derived from the peak strength) of sand sifted from a height of 20 cm is 41.47°, and pouring that sand from the same height resulted in an angle of 37.97°. The height and granulometry variations produced minimal differences of approximately 1° in the angle of peak internal friction.

The stress–strain curves of the shear stress plotted as a function of time for the sand sifted and poured from the same height are presented in Fig. 1. In the sifted sand, the peak strength is substantially higher than that of the poured sand, at values of 2254 Pa and 1996 Pa, respectively (for the highest normal load of 2400 Pa). The dynamic stable strength and the reactivation peak strength, however, vary only slightly. Consequently, the poured sand has a lower rate of strain softening (measured as the difference between the coefficient of peak friction and the dynamic–stable friction divided by the coefficient of the dynamic–stable friction) (Table 1) than the sifted sand.

Table 1 also shows that the two filling techniques produce differences in the cohesion strength of the materials. At peak friction, the cohesion of the sifted sand ranges between 57.3 Pa and