BRIEF COMMUNICATIONS

Packing grains by thermal cycling

Small temperature changes can affect the packing of granular materials without mechanical disturbance.

A long-standing problem in managing the behaviour of a collection of solid grains concerns the nature of the grain packing[1], a property that is typically controlled by how the grains are poured or shaken. Here we show that a systematic and controllable increase in granular packing can be induced by simply raising and then lowering the temperature, without the input of mechanical energy. This thermal processing may have important practical implications for the handling and storage of granular materials.

The packing fraction of a granular material is defined as the fraction of sample volume that is filled by grains rather than by empty space, and typically varies between 57% and 64% for randomly arranged, spherical grains and even more widely for other grain shapes. The density of packing can be increased by vibration or tapping, which induce small rearrangements that allow the grains to settle[2–4].

When a granular material is heated, the grains and their container both undergo thermal expansion. This can lead to settling because of the metastable nature of disordered grain configurations (especially if the grains and their container are made of different materials), and such settling should not be reversible upon cooling to ambient temperature. It has been shown that temperature changes affect silos in industrial settings[5,6] and the stress state of a granular pile[7,8]. But the grain dynamics induced by thermal cycling have not been analysed until now.

We examined the change in packing fraction for glass spheres contained in vertical plastic cylinders in response to thermal cycling (using both single thermal cycles from room temperature and repeated cycles over the same temperature range; for methods, see supplementary information). We found that there was a clear increase in packing even for a single cycle to 10 °C above ambient room temperature (Fig. 1a). The results were not affected by the height to which the cylinders were filled (to within ±10%), the heating rate, or the time spent at the cycle temperature after thermal equilibrium was reached. They changed only slightly (<20%) if the cylinder diameter was changed by an order of magnitude (Fig. 1b). This latter result is physically sensible, because the expansion of the grains and of the container scales with the size of the sample.

The packing fraction continues to increase over multiple thermal cycles (Fig. 1c). The increase can be described by a double-exponential density-relaxation model, consistent with a combination of large-scale (relaxation of granular blocks) and small-scale (relaxation of individual particles) rearrangements (for details of the model and fits to the data, see supplementary information)[9]. Although the limited range of the experimental data restricts thorough testing of this double-relaxation model, the 'time constants' of the two different relaxation times observed for each cycle temperature do increase with decreasing cycle temperature — consistent with smaller thermal expansion, as more cycles are needed to achieve the same change in packing fraction at a lower cycle temperature.

The primary cause of the changes in packing fraction noted here is probably the difference between the thermal expansion of the container and of the grains. This explanation is confirmed by our observation (results not shown) of similar changes in packing of plastic spheres in glass cylinders (where the grains expand more than the container), and of smaller changes in packing for glass spheres contained in glass cylinders.

Our results indicate that there may be many thermal effects in granular media, analogous to the effects of vibration. For example, a geophysical form of granular segregation ('stone heave') has been associated with thermal effects[10]. Temperature changes can also cause granular pressure to increase in outdoor silos with each diurnal cycle — potentially leading to catastrophic failure of the silo[6]. Our results demonstrate that thermal cycling can provide an almost 'adiabatic' alternative to mechanical agitation for altering grain packing.

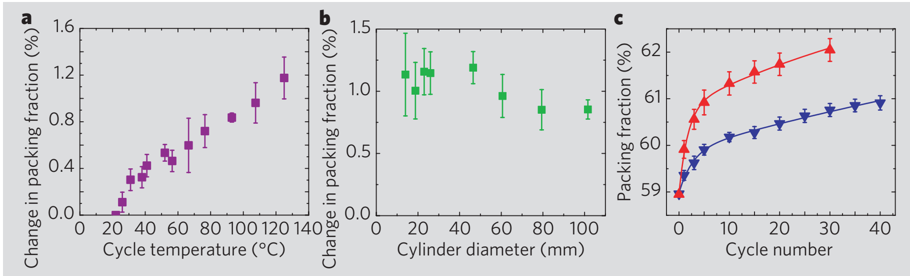

Figure 1 | Change in packing fraction with thermal cycling for glass spheres in a plastic cylinder. **a**,**b**, Change in packing fraction as **a**, a function of cycle temperature from room temperature for a single cycle (cylinder diameter, 60.6 mm) and, **b**, a function of cylinder diameter for a single cycle (cycle temperature, 107 ± 2 °C). **c**, Change in packing fraction after multiple thermal cycles (cycle temperatures: red, 107 ± 2 °C; blue, 41 ± 1 °C). Lines represent fits of the data to a double-relaxation model (ref. 9; for details, see supplementary information). Error bars represent the standard deviation determined from several repeated measurements (**a**,**b**, 12 or more measurements; **c**, 6 measurements).

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CORRIGENDUM

Animal communication: Complex call production in the túngara frog
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The bar coloration as specified in Fig. 1a of this communication is misleading: it should indicate the relative amplitude of odd-to-even harmonics before (red bars) and after (blue bars) treatment for the 'chuck' and 'whine' call components.
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