

Chapter 14

Analysis of the Thermomechanical Response of a Rubber-like Granular Material



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Abstract Infrared thermography was used to study the thermal signature of a rubber-like granular material subjected to cyclic confined compression. The discrete medium consisted of cylinders placed in parallel. A fluctuation of the temperature at the same frequency as the mechanical loading was observed, as well as a global self-heating as the cycles progressed. This can be associated with the thermoelastic coupling effect and the mechanical dissipation effect, respectively. The thermoelastic coupling effect is visible in all contact zones between the particles, which can be explained by the stress concentrations that occur there. A strong mechanical dissipation effect occurs at specific contacts, which can be explained by the high friction between certain particles.

Keywords Granular material · Rubber-like material · Infrared thermography · Thermoelastic coupling · Intrinsic dissipation

14.1 Introduction

Granular materials are omnipresent around us, in many industrial fields and in many natural phenomena. Rice and sugar are used in the food industry and in our daily lives. Sand and rocks are commonly used in civil engineering for the construction of buildings or streets. Granular flows are involved in avalanches and landslides. In the context of engineering, granular materials can be defined as a set of solid particles whose macroscopic mechanical behavior is governed by interparticle forces, i.e., contact forces between particles. Granular media are generally made up of grains having various distributions in terms of size, shape, and base material. This leads to a variety of mechanical phenomena that are not yet clearly understood. Numerical simulations have been widely used to study the influence of parameters such as particle shape, density, polydispersity, elasticity, and friction [1]. Several experimental techniques are also available. For measurements in the volume, we can mention X-ray tomography [2]. For surface measurements, particle image velocimetry and digital image correlation are widely used [3–9]. Stress fields can be obtained by photoelasticity measurement using particles made of birefringent materials [10–12]. Mechanoluminescent materials have also been used to visualize the intensity of interparticle contacts [13]. In most of the studies available in the literature, the particles are rigid or hard. Contact stiffness is then the main parameter. A granular system consisting of soft matter is more complex to analyze. Recently, the compaction of highly deformable particle assemblies has been performed numerically in Ref. [14], opening the possibility of comparison with experimental results for soft granular materials.

Infrared (IR) thermography has also been used to measure the thermal signature of the mechanical response of soils and sands [15–17]. Some studies have mainly focused on Schneebeli materials (two-dimensional discrete media made with

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cylinders) in order to analyze the contact zones between the particles, i.e., the stress concentration zones [18–22]. In the present study, IR thermography was used to analyze the thermal response of Schneebeli media made of thermoplastic polyurethane (TPU). Temperature changes were measured with an IR camera during cyclic confined compression. The objective was to distinguish the thermoelastic coupling effect (associated with reversible mechanical behavior) and the mechanical dissipation effect (associated with irreversible mechanical behavior).

14.2 Experimental Preparation

The experimental setup is presented in Fig. 14.1. A granular sample was prepared by randomly placing cylinders with elliptical cross-section into a rectangular metallic frame: see the schematic view in Fig. 14.1a. The particles were made of TPU manufactured by using an in-house device. Each particle was molded at ambient temperature in a vacuum chamber to avoid bubble formation. One side of the elliptical face of each cylinder was polished to obtain a smooth surface perpendicular to the longitudinal axis. To maximize the thermal emissivity of the surfaces observed by the camera (and thus reduce reflections in the IR range), a matt black paint was sprayed on the particle cross-sections as well as on the frame containing the granular system. Black curtains and cardboards were also placed around the device (not visible in Fig. 14.1b) to minimize parasitic reflections.

A cyclic triangular compressive loading was applied on the top of the granular system by using a Zwick/Roell ZMART PRO testing machine through a pusher (see Fig. 14.1b). The minimum and maximum forces were set to -1200 N and $-12,000$ N, respectively. The loading was force-controlled with a force rate equal to 900 N/s, leading to cycle duration of 24 s. Note that some preliminary mechanical cycles were applied in order to compact the granular system. Next, the minimum force was kept constant for about 10 min to ensure that a steady thermal equilibrium of the system was reached before starting the cyclic loading.

A Cedis Jade III-MWIR camera was utilized to capture the temperature fields on the surface of each elliptical particle during the mechanical loading at a recording frequency of 10 Hz. In practice, the base acquisition frequency of the camera was set to 100 Hz with a real-time averaging every ten images in order to improve the thermal measurement resolution. The resulting standard deviation of the thermal noise (measurement resolution) was lower than 0.01 °C thanks to this real-time average operation.

Temperature maps were also captured during 5 seconds just before the beginning of the cyclic loading in order to define the reference temperature field. Figure 14.2a shows the field of temperature differences at the beginning of the mechanical test with respect to this reference thermal state in order to reveal the spatial noise during the test. The corresponding distribution of the values within the particles (i.e., excluding the voids between the particles) is displayed in Fig. 14.2b. Values lower than about -0.04 °C are due to pixels near the boundary of the particles. The standard deviation of the distribution within the $[-0.04$ °C; 0.04 °C] range is equal to 0.012 °C.

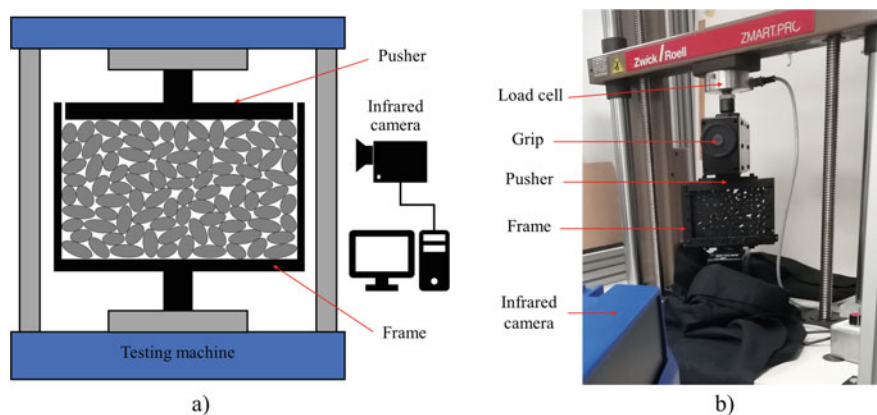


Fig. 14.1 Experimental setup: a) schematic view, b) picture of the experiment

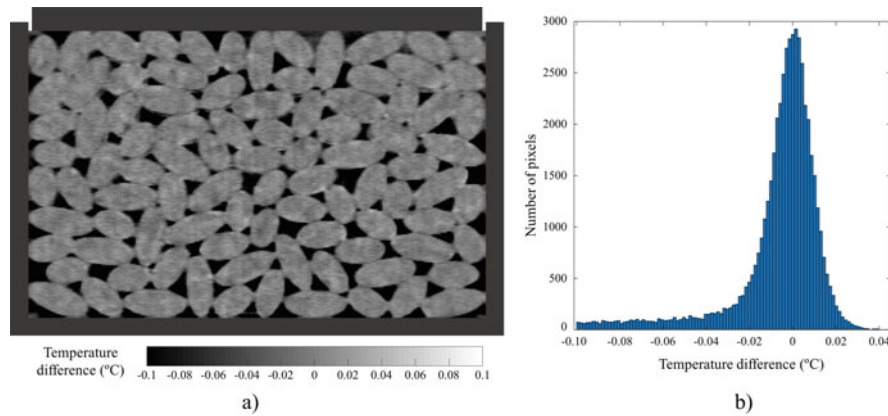


Fig. 14.2 Thermal noise: (a) temperature differences at the beginning of the cyclic loading with respect to the reference temperature field, (b) corresponding distribution for the pixels within the particles

14.3 Thermomechanical Background

Thermomechanical couplings in materials can be separated into two different parts, namely a part associated to *reversible* processes (elasticity) and a part associated to *irreversible* processes (e.g., plasticity, viscosity, fatigue damage, friction):

- The first case is called *thermoelastic coupling*. Two types of coupling between temperature and strain must be considered according to the physics associated with elasticity: *isentropic* coupling governed by thermal expansion or compression; and *entropic* coupling governed by the degree of disorder. In rubber-like materials, entropic coupling becomes dominant over isentropic coupling as soon as the level of deformation is greater than 10% [23].
- In the second case, the associated calorific quantity d_1 (in W/m^3) is called *mechanical dissipation* or *intrinsic dissipation*. It is worth remembering that it is different from the thermal dissipation d_2 , the two types of dissipation being involved in the Clausius-Duhem inequality $d_1 + d_2 > 0$.

Mechanical dissipation can be revealed through the temperature change over integer numbers of mechanical cycles. Indeed, heat quantities due to reversible mechanical phenomena are null over a thermodynamical cycle. More precisely, the heat quantities upon loading and unloading are equal in magnitude but opposite in sign. On the contrary, the mechanical dissipation is positive whatever the loading evolution: $d_1 > 0$. Thermoelastic coupling is a “strong” coupling. Indeed, the corresponding heat power density is much higher in magnitude than the mechanical dissipation in most cases. Extracting mechanical dissipation effect from the global thermal response of the material is in general possible for a cyclic loading, for which thermoelastic coupling effect vanishes cyclically. Moreover, the heat produced by irreversible phenomena accumulates over the cycles (because d_1 is always positive), which helps to experimentally identify this quantity. In the present experiment, thermoelastic coupling was evidenced by considering half of the first mechanical cycle (assuming that the mechanical dissipation is low over this duration) whereas mechanical dissipation was highlighted by considering ten cycles.

14.4 Analysis of the Reversible Mechanical Phenomena

Figure 14.3 shows the temperature change field at the half of the first mechanical cycle. “Hot” zones are clearly evidenced at each contact between the particles. They are also visible at the contacts with the metallic frame. They are logically due to the stress concentrations resulting mainly a priori from the normal interparticle forces. The largest temperature increase is observed in the upper left corner of the granular material. Tangential forces may be also involved in this zone, as revealed by the analysis of the thermal signature of the irreversible mechanical phenomena in the next section.

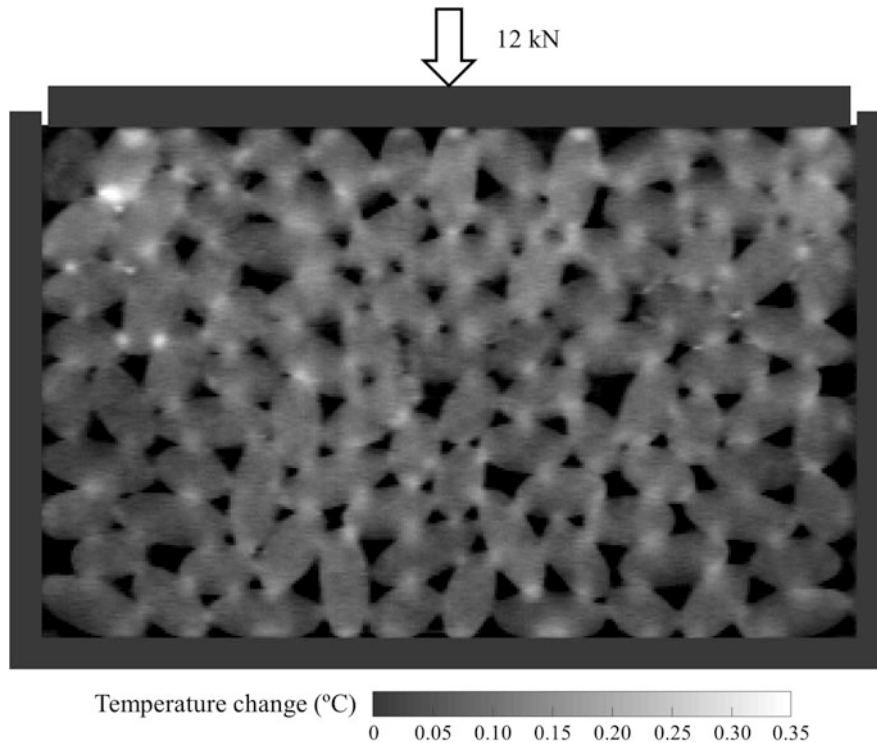


Fig. 14.3 Field of temperature change at the half of the first mechanical cycle, evidencing the thermoelastic coupling effect at the interparticle contacts in the granular system under confined compression

14.5 Analysis of the Irreversible Mechanical Phenomena

Figure 14.4 presents the field of temperature change at the end of the tenth mechanical cycle. Based on the assumption that the heat quantity due to the thermoelastic coupling is null over the preceding successive mechanical cycles, this map displays a thermal signature of the mechanical dissipation effect, i.e., of the irreversible mechanical phenomena. In granular media, this latter quantity can be mainly associated to friction at the contacts. However, viscosity and damage in the volume can be also involved, especially in the zones subjected to high stress levels. Figure 14.4 clearly shows that the mechanical dissipation effect is not present at all the contacts, which strongly differs from the case of the thermoelastic coupling effect (compare with Fig. 14.3). “Hot” zones are now mainly visible only in the upper two corners of the granular system. This can be explained by the greater movement of the particles in the upper two corners, potentially leading to greater friction. It can also be observed that the size of the “hot” zones is quite large, which can be explained by the heat diffusion over the ten cycles.

Finally, Fig. 14.5 shows the variation in time of the temperature at a given interparticle contact located in the upper left part of the granular material: see point A in the schematic view. As expected, the temperature oscillates at the same frequency as the mechanical loading. It can be seen that the mean temperature change first increases over the cycles and then stabilizes from nearly the seventh cycle: see the red dashed curve. This increase can be attributed to the monotonous production of mechanical dissipation over the cycles. The stabilization results from the equilibrium between the heat produced by the mechanical irreversible phenomena at point A and the heat diffused to the environment of point A.

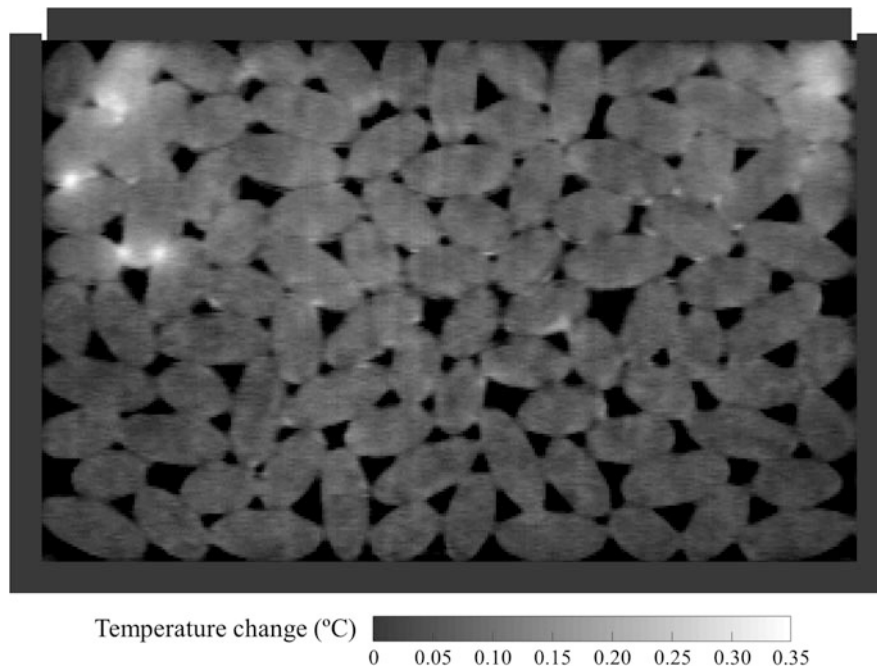


Fig. 14.4 Field of temperature change at the end of the tenth mechanical cycles, evidencing the mechanical dissipation effect especially in the two top corners of the granular material

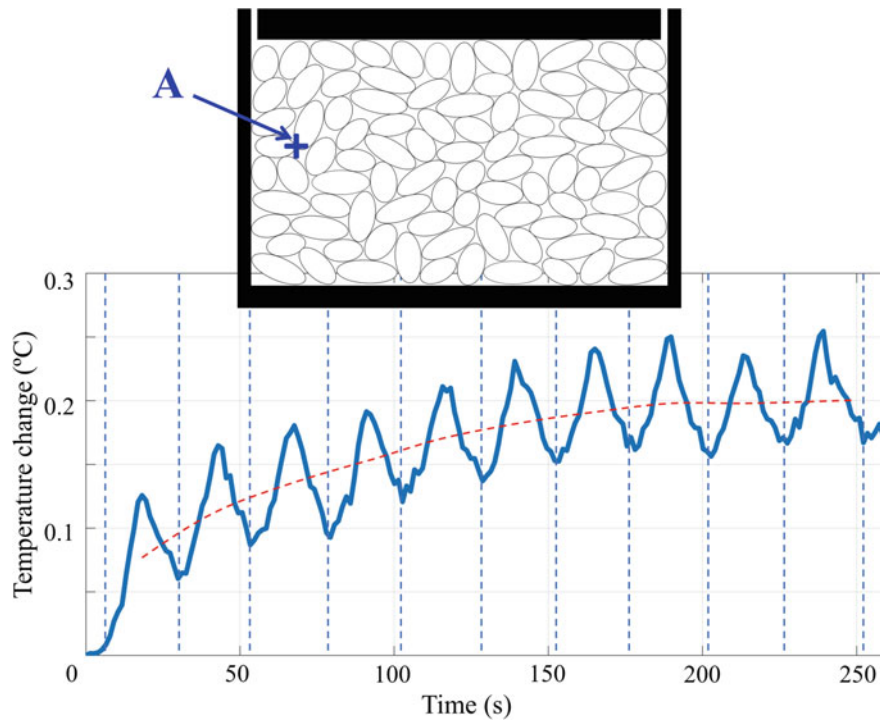


Fig. 14.5 Temperature variation at the interparticle contact point A along the cyclic loading (blue curve). The red dashed curve corresponds to the global self-heating

14.6 Conclusion

IR thermography is in principle applicable to analyze thermomechanical phenomena of any types of material. However, it remains difficult to apply to cohesionless granular materials, which explains the small numbers of studies published in the literature (see Refs [15–22]). The objective of this study was to analyze the thermomechanical response of a two-dimensional granular system made from TPU cylinders with elliptical cross-section. A cyclic compression loading was applied to a granular system while an IR camera measured the resulting temperature changes. The thermoelastic coupling effect and the mechanical dissipation effect were distinguished in the thermal response. The thermoelastic coupling effect is clearly visible in the contact zones between the particles, which can be explained by the stress concentrations occurring there. The mechanical dissipation effect manifests itself in specific contacts, which can be explained by the high friction between certain particles.

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