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Decoding force transmission in industrial granular materials via vibration-induced densification

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Abstract. The behaviour of grain assemblies involves nonlinear and inelastic phenomena that link microscopic grain properties to macroscopic flow behaviour. This connection is mediated by the mesoscale, specifically the contact network, which remains especially difficult to access in real, cohesive industrial powders due to their heterogeneity, opacity, and fine particle size. In this study, we investigate vibration-induced densification under controlled excitation conditions, tracking packing fraction dynamics up to the onset of decompaction. We find that the force required to trigger decompaction correlates with interparticle cohesion, and appears to mark a transition in bulk structural stability. Based on this, we define a dimensionless adhesion number, $A_d = F_d/W_p$, where F_d is the decompaction force and W_p the powder weight. A_d offers a force-based descriptor of bulk cohesion and may reflect underlying structural transitions at the mesoscale, a scale that remains challenging to access directly in industrial powders.

1 Introduction

Granular materials such as sand, wheat, and wood have long played essential roles in human activities and remain central to industrial processes. Since the Industrial Revolution, engineers have faced challenges in handling and processing grains, particularly due to flow-related issues. Poor flowability can lead to complications such as segregation, feeder blockages, rathole formation, and even silo collapse during storage.

The behaviour of granular assemblies is inherently complex, governed by nonlinear, inelastic, and highly dissipative interactions. In this context, while the macroscopic response is rooted in microscale mechanisms, it is at the mesoscale — through the contact network — that this connection is established. Although force-network evolution and statistical properties have been extensively studied in idealised systems, force transmission in industrial powders is far more intricate. Irregular particle shapes and cohesive interactions complicate any direct link between microstructure and bulk behaviour, unlike in model systems composed of non-cohesive, spherical grains [1,2].

This work aims to extract force network information from industrial granular assemblies under vibration-induced densification experiments. The compaction of granular materials is a common unit operation across various industries, including pharmaceuticals, cosmetics, metallurgy, agro-food, nuclear, and automotive. It is employed to create products such as agglomerates, capsules, tablets, pellets, and battery electrodes—all designed with specific compositions, porosities, shapes, and strengths. Force transmission and the resulting contact network are essential aspects that evolve throughout the compaction process.

Inspired by the pioneering work of Knight—the Chicago experiments [3]—our methodology focuses on tracking the evolution of the packing fraction during vibration as a function of the energy supplied to the system [4], until the powder bed undergoes decompaction or fluidization [5]. A dimensionless number that characterizes decompaction as a regime change is extracted. Our initial findings suggest that the parameters governing decompaction may provide meaningful insights—both as a descriptor of bulk cohesion and as a macroscopic indicator of the point beyond which the force network loses structural integrity. This approach represents a significant step forward in our ongoing efforts to gain deeper understanding of the complexities of industrial granular materials.

2 Industrial Powders and Methodology

2.1 Powders

Several industrial powders were selected to represent a broad range of application domains and physical characteristics, with mean particle sizes ranging from 9 to 300 μm. The selection includes materials used in the pharmaceutical, food, and construction industries, as well as technical powders such as monodisperse and industrial-grade glass beads as large as 1 mm [4,5]. This diversity ensures that the analysis captures a wide spectrum of flow behaviours, morphologies, and

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cohesive properties, beyond what can be observed in model granular systems.

2.2 Experimental set-up

The experimental setup consists of an electromagnetic shaker coupled to a cylindrical borosilicate glass vessel (26 mm in diameter, 240 mm in height). Both excitation signals and data acquisition are managed via LabVIEW, with excitation parameters such as frequency and amplitude set through the interface. The shaker provides a continuous sinusoidal excitation. The force supplied to the powder is measured by a sensor bolted between the shaker and the vessel. The system's acceleration—including both shaker and vessel—is measured by a side-mounted accelerometer, as shown in Fig. 1. Both, the force and acceleration signals are described by their peak-to-peak amplitude. The powder bed evolves under free surface conditions, with no mechanical constraint or applied load. Packing fraction evolution is extracted from the powder bed height using image analysis with a high-speed camera [4,5].

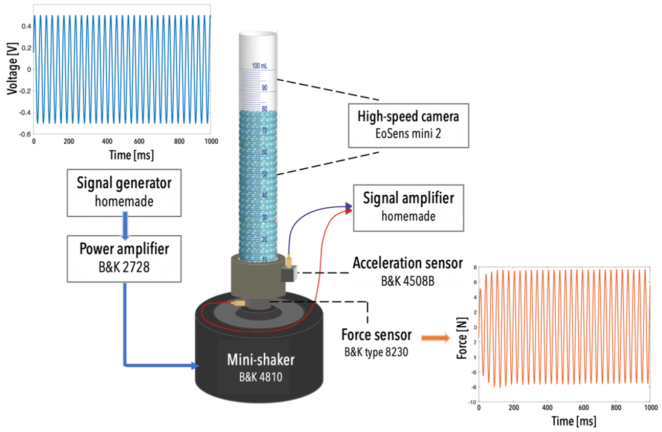

Fig. 1. Schematic representation of the harmonically driven vibration experiments, showing the particle damper, the excitation system and data acquisition sensors. Representative signal traces are shown: the generator excitation voltage (blue, top right), and the measured force (orange, bottom left).

The densification dynamics is studied though the relative acceleration, Γ, that compares the imposed acceleration to gravity ($\Gamma = a/g$). The compactness of the granular system under vibration is quantified using the packing fraction ϕ.

2.3 Methodology

The methodology consists of pouring the powder into the vessel using a funnel. Densification is then initiated by increasing the acceleration of the imposed motion in steps at a fixed frequency (Fig. 2). Each acceleration is maintained until the powder bed stabilizes for at least 5 minutes. This densified state is referred to as 'stable compactness', $\phi_{s,i}(\Gamma_i)$. An entire experiment consists of studying $\phi_s = f(\Gamma)$ until the powder bed undergoes decompaction—marked by a reversal in the packing fraction trend, indicating refluidization (star data point (a_d, F_d, Γ_d) in Fig. 2). Decompaction may occur either gradually—through a convection-like motion that draws air into the powder bed (mostly for larger and/or low cohesive particles)—or abruptly, producing a powder cloud that hinders accurate volume measurement.

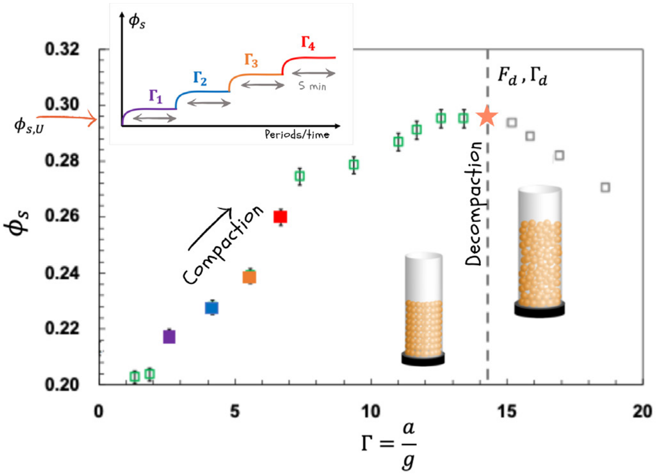

Fig. 2. Schematic representation of compaction behaviour as a function of the vibration relative acceleration applied to the powder bed. The star indicates the acceleration level at which decompaction occurs.

3 Decoding decompaction

It is commonly acknowledged that the probability of reproducing the same particle distribution after pouring and during vibration is extremely low, if not impossible. Despite this, we consistently achieve a highly reproducible initial powder height, and thus packing fraction. In addition, in a series of experiments using different subsamples from the same bulk powder—each prepared under identical environmental and excitation conditions—we observed that the packing fraction evolution, $\phi(t)$, remained remarkably consistent across vibration cycles, with less than 2 % variability [4]. Image analysis revealed that particles within the bulk appeared to move differently—creating distinct void patterns. However, the system consistently converged toward the same packing fraction (Fig. 3). Weakly connected grains within the bulk seem to behave in a liquid-like manner [4,5], while the overall system appears to be held together by a solid-like structure, and trapped air within the bulk seems to escape toward the surface through these more mobile regions.

The complexity of volume changes in granular materials underscores the need to identify macroscopic indicators that can reveal meaningful aspects of the system's internal dynamics. It should be noted that, to date, no existing method, whether DEM simulations, photoelastic imaging, X-ray tomography, or grain-scale force sensing, has proven applicable or robust for characterizing force networks in industrial cohesive powders. These materials are fundamentally challenging due to their heterogeneity, opacity, and fine particle size. In this context, the conditions required for the decompaction of a vibrating bed appear to be pivotal.

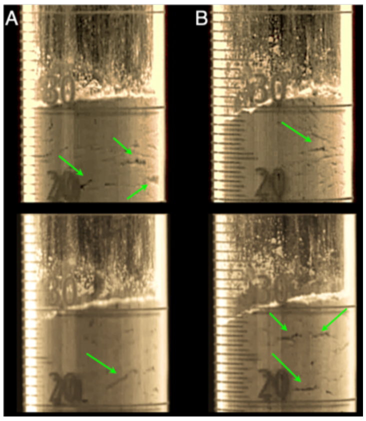

Fig. 3. Snapshots from two separate compaction dynamics experiments, A and B, on different samples of the same powder under identical vibration conditions. The images, captured at synchronized intervals, compare the dynamics at two different moments (top and bottom sets). Green arrows highlight differences in particle rearrangement within the bulk.

Indeed, if the decompaction thresholds (Γ_d, F_d) are applied to a granular material regardless of its initial packing state, the powder bed will not compact further. Instead, a fluid-like behaviour—whether liquid-like, gas-like, or both—will be observed, indicating an unstable state.

Thus, these experimental findings suggest that the parameters governing the decompaction of a powder bulk may offer access to the mesoscale, capturing a macroscopic threshold for the stability of the contact network. In this context, F_d *serves both as a descriptor of bulk cohesion and as a macroscopic indicator of the point beyond which the force network loses structural integrity*.

A dimensionless number, A_d, can be defined at the decompaction threshold as the ratio of cohesive forces to non-cohesive forces:

$$A_d = \frac{F_d}{W_p} \qquad (1)$$

A_d is analogous to a Bond number of the mesoscale, quantifying bulk adhesion as the ratio of decompaction force F_d—measured via a sensor coupled to the base of the vessel—to the gravitational weight of the powder placed in the vessel, W_p.

The decompaction force relies on both the vibration wave (its shape and intensity, Γ, as well as the period between cycles) and the system geometry (container dimensions, grain size, and powder height). For cohesive powders, these parameters play a crucial role, as different combinations can lead to different compaction behaviours. This implies that various configurations can be explored, each corresponding to specific conditions under study. Nevertheless, a *maximum packing fraction* $\phi_{U,}$ can be identified for a given system configuration, representing the highest achievable reorganization state of the powder in a vessel. This configuration defines what we refer to as the 'Ultimate' state. The value of $\phi_{U,}$ is intrinsic to the system (powder + vessel) and appears to correlate more closely with the powder's flowability when assessed through compactness-based indices, such as the Hausner Ratio (HR)— the ratio of final bulk density (after vibration) to initial bulk density (after pouring) [6]. All parameters describing this Ultimate state are denoted by the subscript U (e.g., $A_{d,U}$, $F_{d,U}$ and HR_U [6])

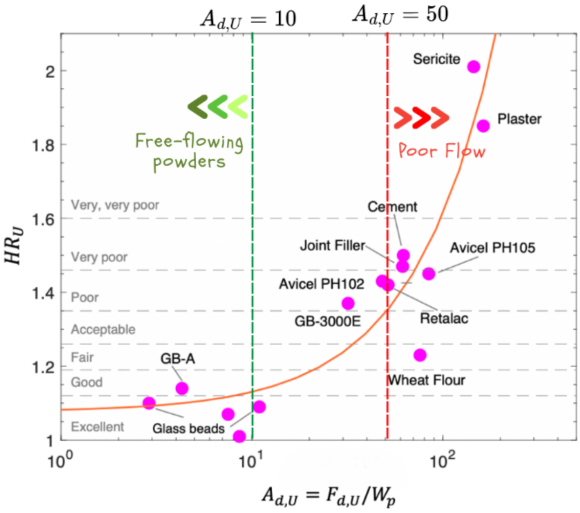

Fig. 4. Evolution of $\boldsymbol{HR_U}$ with $\boldsymbol{A_{d,U}}$ both determined from the experiments where the highest packing fraction was obtained. The y-axis shows the Hausner classification of flowability.

The correlation between the ultimate Hausner ratio (HR_U) as a flowability indicator and the adhesion number ($A_{d,U}$), both obtained from vibration-induced densification experiments (30 g of powder, 20% RH), is shown in Fig. 4. Although plotted on a semi-logarithmic scale, the HR_U values exhibit a clear linear relationship with $A_{d,U}$. These results support our hypothesis: lower A_d values correspond to weak force networks dominated by the powder's weight, with $A_d < 10$ indicating free-flowing behaviour, while higher A_d values reflect stronger internal networks that hinder flow, with $A_d > 50$ being associated with poor flowability (Fig. 4).

To further relate compaction and decompaction forces to powder cohesive behaviour, bulk cohesion, c, was determined from the yield locus using the FT4 powder rheometer, following the Mohr-Coulomb plasticity criterion:

$$|\tau| = \mu\,\sigma + c \qquad (2)$$

where μ is a friction coefficient, σ and τ represents normal and shear stresses.

The FT4 operates as a torsional shear cell [7]. The powder is placed in a cylindrical vessel of 25 mm diameter and 10 mL volume, with a normal force applied through a roughened lid. Shear is induced by rotating the lid while torque is recorded (see Fig. 5.a). For each yield locus, the powder is first consolidated under a defined normal stress (preshear), then sheared to failure under lower consolidation stresses. The internal yield locus is obtained by the linear regression from the resulting stress pairs (σ, τ).

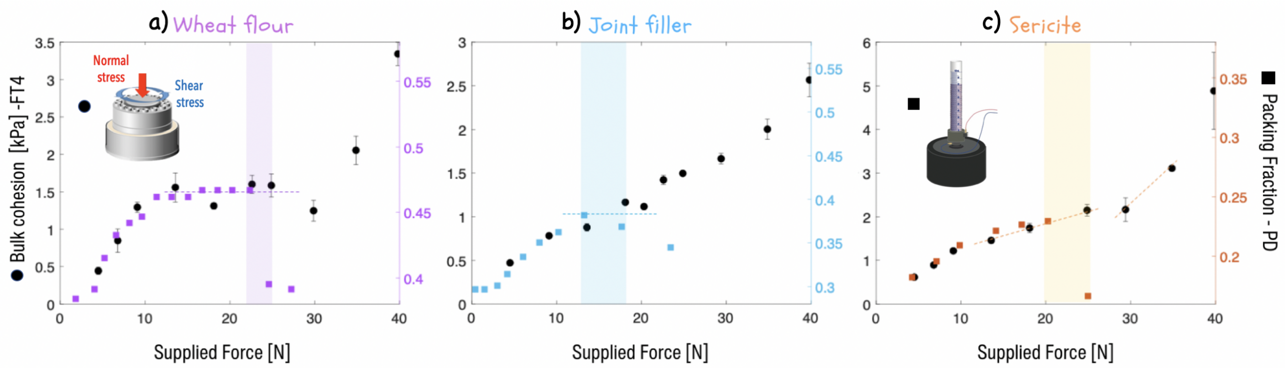

Fig. 5. Evolution of bulk cohesion c (black circles left axis) and packing fraction (coloured squares, right axis) as a function of the supplied force for three powders: Wheat Flour (left, purple), Joint Filler (center, blue), and Sericite (right, orange). Measurements were obtained using an FT4 powder rheometer for c (circles) and a particle damper for ϕ_s (squares). Shaded regions indicate the onset of decompaction.

Figure 5 shows bulk cohesion and packing fraction evolution under similar applied force conditions. In the case of the FT4, for bulk cohesion, the supplied force for each data point (circles) corresponds to the preshear stress—i.e., the major consolidation stress used to construct the corresponding yield locus. For the particle damper (vibrational densification under free-surface conditions, Fig. 1) it corresponds to the force supplied to the powder—i.e., the peak-to-peak amplitude of the force measured by the force sensor. Two main observations can be highlighted from this analysis. First, in general, more cohesive powders require greater applied force to initiate decompaction. However, cohesion does not appear to be the sole parameter controlling the onset of decompaction [5,6]. Second, the applied force at which decompaction occurs in the particle damper consistently coincides with a marked change in the trend of the bulk cohesion curve. This suggests the occurrence of a structural transition in the granular packing, even under constrained conditions.

4 Conclusions

This study investigates the dynamics of vibration-induced densification across a broad range of industrial powders, focusing on the conditions leading to compaction and, ultimately, decompaction. The results indicate that the force required for decompaction counteracts interparticle cohesion, thereby disrupting stable contact networks. These thresholds appear to mark structural transitions within the material, potentially reflecting the limits of force transmission.

To capture this behaviour, we propose a dimensionless adhesion number A_d as a practical tool for characterizing bulk cohesion in non-ideal granular systems. While the precise connection between this macroscopic threshold and microscopic features—such as network anisotropy—remains to be theoretically demonstrated, our results provide compelling correlations and raise promising hypotheses. In particular, the decompaction threshold may serve as a macroscopic signature of the mesoscale force network, offering experimental access to a scale that remains otherwise difficult to probe. At this stage, our methodology offers one of the few experimental pathways for probing such transitions in cohesive industrial powders from a force-based, macroscopic perspective.

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