

**IFPRI**  
**Research Project Brief**  
**Aeration and Deaeration of Geldart Type C powders**

Controlling Adhesion between Particles  
for a better understanding of  
Rheology and Aeration of Powders.

CAPRAP

- **Principal investigator (PI):** Olivier Pouliquen
- **Host institution:** Aix Marseille University-CNRS, France
- **Proposal duration:** 36 months

This proposal follows the first IFPRI project we proposed on the rheology of cohesive model systems and its application to the compaction and aeration of powders. In this project, we developed techniques to control adhesion between particles and established a methodology to study their rheology under low confinement in the inertial regime. The final year of the project will be dedicated to a detailed study of the rheology and compaction of the model materials. The new project we are proposing continues along the same lines and results from discussion with the partners during the liaison meetings. The aim is to apply the methodology developed during the first phase, for model materials and simple configurations, to setups or materials closer to industrial applications. Specifically, the project will explore the link between our rheological approaches using shear cells and the powder rheometers commonly employed to study powders under low confinement, such as helical stirrers (FT4) and flow in rotating drums. A particularly challenging aspect will involve adapting our shear cell to finer materials to enable the study of industrial powders. Finally, the project will focus on the role of coupling with air, a question that was initially planned for the first project but could not be addressed due to time constraints.

## A. Summary and achievement of the first two years.

The program of the first IFPRI project were organized into five main steps:

1. *Development of Model Materials*: the goal was to create particle systems where adhesion can be controlled and, if possible, the stiffness of the particles can also be tuned.
2. *Characterization of Particle Properties*: the goal was to develop experimental techniques to accurately measure key particle properties, such as adhesion and friction.
3. *Bulk Rheology Measurements*: The goal was to design and implement a system capable of measuring the bulk rheology of powders under low confinement stresses and in the inertial regime.
4. *Study of Flow Configurations*: The goal was to investigate flow configurations relevant to packaging processes, including silo flow, flow around obstacles, and compaction under vibration.
5. *Coupling with Air*: The goal was to address the role of air-particle interactions in powder flow dynamics.

### *The development of the tools:*

Following this program, during the two first years of the project we have developed different methodologies. We have proposed two methods to control adhesion forces in a granular medium. The first one is based on coating silica particles with a thin layer of polymers, whose thickness control the adhesive force. The second method is based on synthesizing micro-polymers particles with two different stiffnesses, which can be functionalized thanks to the click chemistry. To properly characterize these model materials, we have designed a home made setup, based on the measurement of the deflection of a cantilever, using the same principle as an AFM but at a larger size suitable for the typical particle size used in our project (between 100 microns and 200microns). We also have built a shear cell mounted on a high precision rheometer, allowing to apply a continuous shear of a very thin layer of materials under low stress in the inertial regime. The different achievements of the project are summarized in Fig. 1.

### *What we have learn:*

Using the tools we have developed, we have begun analyzing both the rheology and the compaction processes of our model materials, a study that will continue during the final year of the current project. The goal is to establish a rheological description of these materials and characterize their compaction properties, aiming to link their macroscopic behavior to the microscopic adhesive properties of the particles. Preliminary measurements of the friction law and volume fraction are presented in Fig. 2a. One key result we aim to confirm is the occurrence of shear weakening in the friction law: for highly cohesive materials, the friction coefficient decreases as the shear rate increases, when plotted as a function of the inertial number. If this observation is systematically validated, it could provide significant insight into the concept of powder flowability, as shear weakening is a primary source of flow instability.

### *What remains to do:*

By the end of the project, in one year, we aim to have developed a rheological description of the flow behavior of our model cohesive materials. This will include a deeper understanding of the role of adhesive forces between particles and the identification of the relevant dimensionless numbers governing the flow behavior. Additionally, we expect to gain insights into the range of volume fractions achievable in packings composed of our cohesive materials.

Most of the initial objectives of the program should be completed by that time, with the exception of the study on the compaction dynamics and the coupling with air, which we plan to address in the

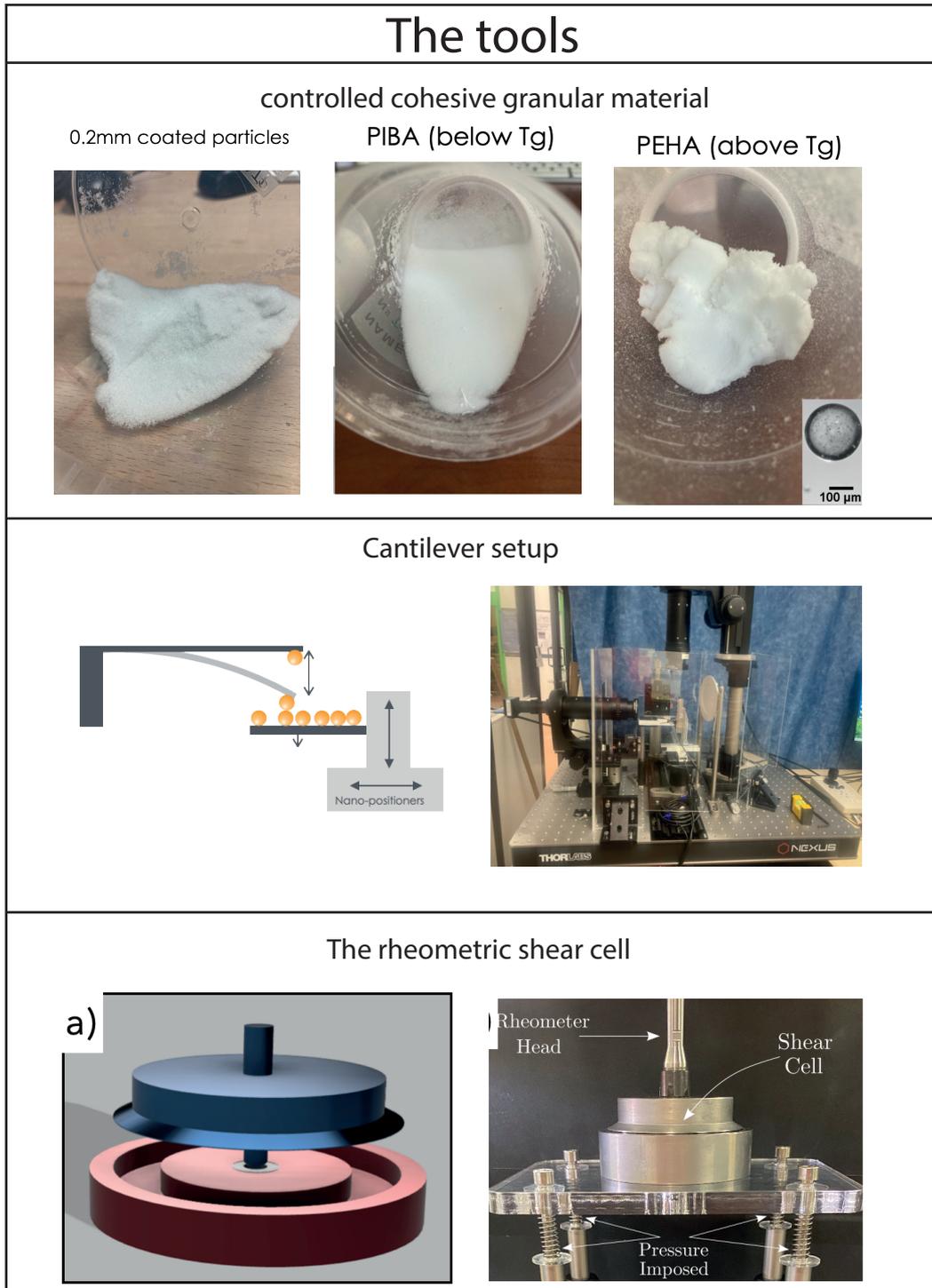


Figure 1: The different tools developed during the first project: model granular materials with controlled cohesive properties; The cantilever setup to precisely measure adhesive forces between particles; the shear cell allowing continuous shearing of a cohesive granular material at low confinement stress.

next phase of the project. Also the next phase should try to adapt the methodology developed in our fundamental approach to configurations closer to the applications.

## B. The research program

Based on the progress made during the first project, we propose to continue our exploration of the behavior of powders under low confinement levels, but focusing on configurations and materials encountered in industrial applications, including aeration and compaction issues. During the IFPRI meetings and our discussions in liaison committees, we gained a clearer understanding of the existing questions in the community and the limited fundamental knowledge we currently have in these regime of flow under low confining situations. Powder rheometers used in the community allow for material characterization, but it remains challenging to relate these measurements to a rheological description and, more broadly, to the concept of flowability.

For the renewal of the project, we propose to explore three questions. The first will involve studying the typical configurations of existing powder rheometers on our model materials in an attempt to link the data obtained from these tools to the constitutive laws identified in our study. The second step will aim to develop a shear-cell-based rheological approach for fine industrial powders (leaving the glass beads model!). Finally, once the rheology of the powder understood, the third step of the project will address the role of air in flows and compaction processes, trying to use two phase flow framework to describe the dynamics.

### *Link between powder rheometers and rheology?*

We propose to focus on three main techniques used to characterize powders flowability properties.

The first configuration is the rotating drum. Typical data recorded during powder characterization with this tool include the dynamics of avalanches, intermittency, and the shape of the free surface. Understanding how flow in a rotating drum changes with varying cohesion in the material and relating these dynamics to the rheological curves observed in a plane shear experiments would be a significant accomplishment. Our main assumption is that the rotating drum configuration is highly sensitive to hysteretic phenomena, meaning that the observed dynamics might be connected to the shear-weakening branch of the constitutive law we have identified. To test this hypothesis, we propose to analyze the flow in rotating drums using our model materials and to link the observed dynamics to the rheology measured in a shear cell. This could represent an important first step toward establishing a connection between rotating drum rheometers and the constitutive equations of powders.

A second commonly used system involves measuring the force and work required to penetrate the powder with a rotating helix. We hypothesize again that analyzing the torque and lift generated during the intruder's rotational motion can provide insights into the constitutive equations of the material. To test this, we propose conducting experiments with our model materials, measuring the forces acting on a moving rotating obstacle, and attempting to relate the results to the rheological curves obtained from shear cell studies.

The last characterization method we aim to revisit from a rheological perspective is the classical "flow function" measurement using a shear cell. The flow function involves measuring how the yield cohesive stress of a powder varies with the applied consolidation stress. While this method focuses solely on plastic properties and does not account for flow dynamics, it is widely used to infer powder flowability. Establishing a connection between flow function measurements and rheological flow properties is a critical step toward developing a coherent framework for describing powder flows. Our model cohesive materials offer a unique opportunity to explore this relationship, bridging the quasi-static transient properties captured by the flow function and the continuous flow rheological properties measured using our specific shear cell.

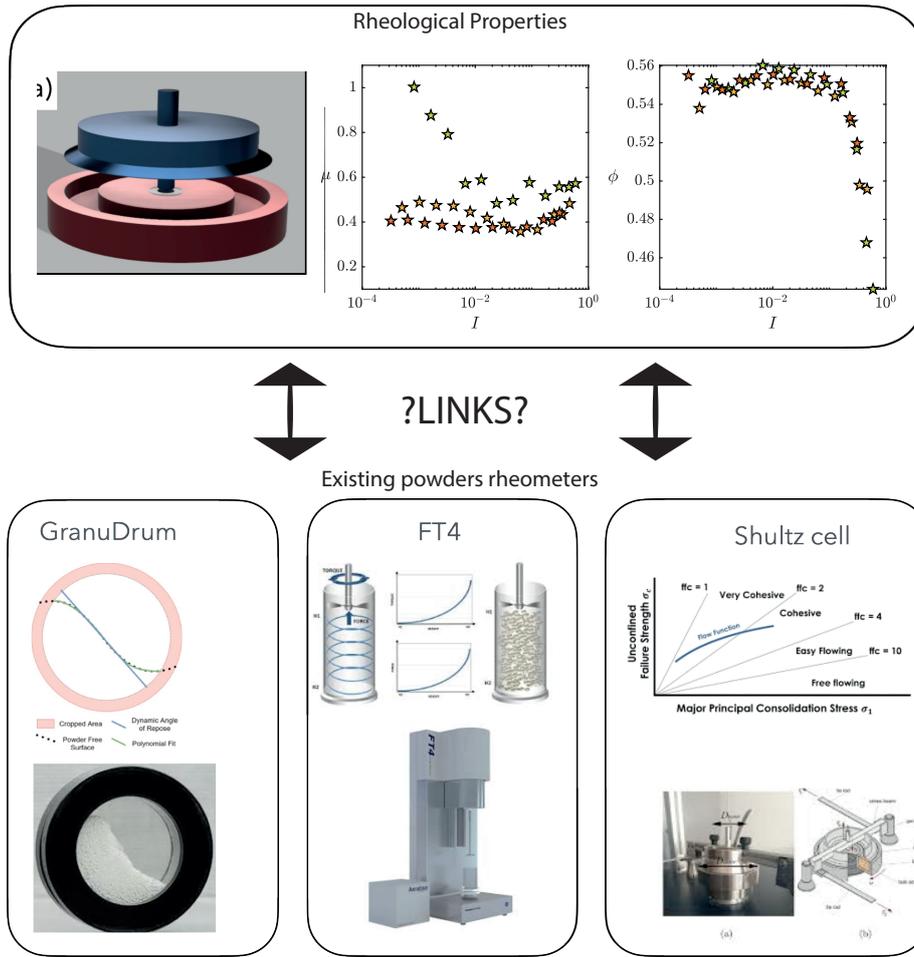


Figure 2: How to link the rheological properties measured in our shear cell, to measurements obtained in other configurations used in the powder community: flow in a rotating drum, force measurement during the penetration of an helix like in the FT4 rheometer, measurement of the flow index in a shear cell.

*How to measure constitutive laws for Geldart C fine powders?*

During the current IFPRI project, we designed a specific experimental setup to accurately measure the rheology of cohesive materials under low confinement stress, expressed in terms of the friction law and volume fraction law. However, the design of the shear cell imposes a limitation: it cannot be used for particles smaller than 150 micrometers. The main challenge lies in the precise adjustment of the cover plate to the annular cell, which is essential to prevent both leakage and blockage in the interstice of the shear cell. Confining a thin powder layer, approximately ten particle diameters thick, under low normal stress and continuously shearing it without losing material through the gap remains a significant challenge. We have several ideas to address this issue, as illustrated in Fig. 3. One approach involves constraining the powder layer outside the sheared region using an air flow. Another idea is to employ a soft elastic ring to laterally confine the powder, but letting the top plate free to press on the powder. By carefully calibrating the additional stress introduced by the ring’s friction, this method could potentially allow the shearing of very fine powders while minimizing the risk of leakage. Although it is uncertain whether these techniques will succeed, they are worth exploring, as the ability to measure the constitutive laws of powders would represent a significant breakthrough.

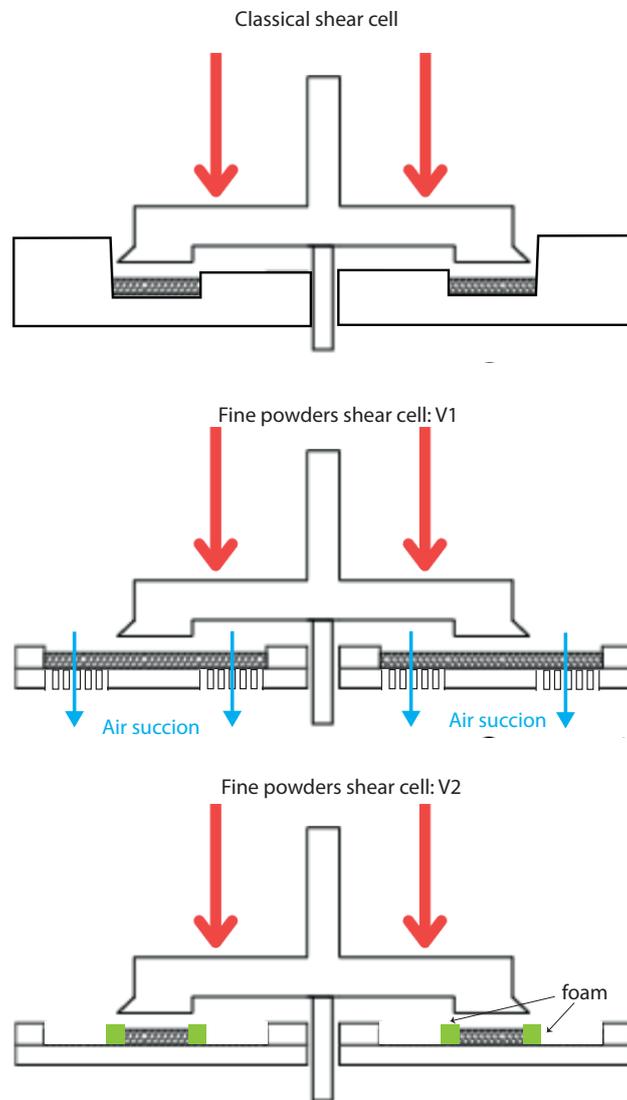


Figure 3: A shear cell for fine powders: a) Sketch of the actual shear cell. The thin powder layer is contained in an annular ring. One experimental difficulty is to prevent leak and jamming in the gap between the rotating top plate and the annular container. b) First version for a shear cell allowing to study rheological properties of fine powders. The idea is to use an air flow to confine the granular layer outside of the shearing region, creating internal walls. c) second version, where the powder is confined in between two soft rings (in green), which prevent the powder from escaping from the shearing region, but let the possibility to impose a normal stress.

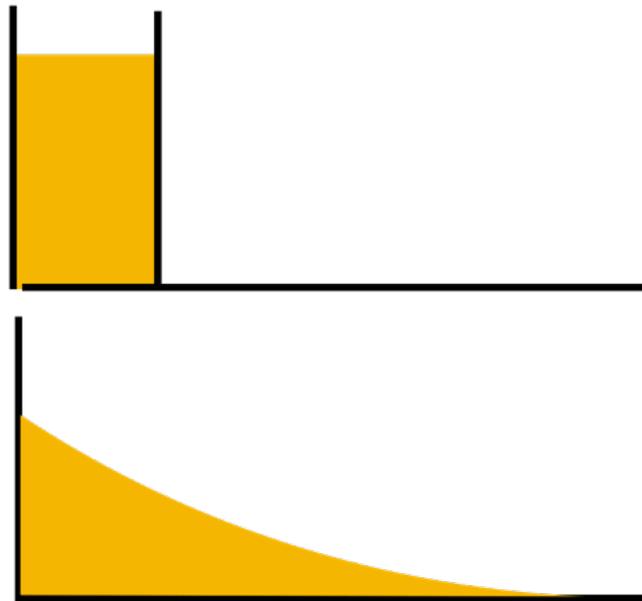


Figure 4: Principle of the granular collapse experiment

*Coupling with air*

A final crucial aspect of the flow dynamics of fine powder particles involves their coupling with air. During handling, air can be entrained within the flow and subsequently trapped in the deposit. This trapped air may influence the deposit’s structure and become a significant source of instability when manipulating filled containers. If mechanical perturbations, flow or vibrations are applied to an initially loose packing, the material tends to compact. During this compaction, air must escape. For fine particles, the movement of air can induce partial or complete fluidization of the material, a transient phenomenon until the packing reaches full compaction. This behavior is analogous to the well-known liquefaction observed in granular media during compaction within a liquid. However, a key distinction lies in the adhesion between particles, which can profoundly alter the material’s response to vibration. On one hand cohesion allows to achieve very loose packings, susceptible to liquefy during compaction. On the other hand, cohesion provides an additional strength that may resist deformation and attenuate the possibility of liquefaction. Our plan is to conduct experiments to study the compaction process while monitoring air pressure dynamics. A first configuration of interest will be the typical granular collapse. By releasing an initially loose packing made of a cohesion controlled granular material, we will be able to understand desaeration. as a function of initial volume fraction, cohesion, and particle size (see Fig. 4). We will also evaluate whether two-phase flow models, commonly used to describe granular fluidization, can effectively capture the aeration behavior of cohesive powders.

*Research program*

	Year 1	Year 1	Year 1
Rheology of cohesive materials	what controls rheology		Link with other rheometers
rheology of Geldart C powders		design of a dedicated shear cell	rheology of fine particles
couling with air	aeration, volume fraction	powder collapse	

### **C. Expected achievements**

This experimental project focuses on understanding the role of cohesion in the flow dynamics of powders. Our aim is to deepen the physical understanding of the flowability of cohesive granular materials and to demonstrate how inter-particle adhesion affects both the rheology and compaction processes of powders. This experimental work is part of a broader project within our group, which also includes numerical and theoretical approaches to powder rheology. The ultimate goal is to develop relevant continuum descriptions for the flow of powders.

### **D. The team**

Our group in Marseille has a strong expertise in granular flows, suspensions and in the rheology of complex fluids. Five years ago we started a long term program on cohesive granular materials, with the hope that the recent progress on dry granular flows we have achieved in the last decade will help us to tackle the much more difficult challenge of the rheology of powders. Beside the fact that we believe that our fundamental approach based on the design of a model material to control adhesion might provide useful information to problem raised in the IFPRI, we are convinced that our research program would strongly benefit from the IFPRI Community. It would give us the opportunity to share our results with imminent colleagues working in the field, but also and more importantly would provide contacts and discussion with engineers from various industries and learn from their unique knowledge of the rich and complex behaviour of powders.