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

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

CAPCAP

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- **Host institution:** Aix Marseille University-CNRS, France

- **Proposal duration:** 36 months

To address the problem of powder packaging raised by the IFPRI research program, we propose a fundamental approach consisting in using a model material, for which the inter-particle adhesion can be precisely controlled. We believe that being able to tune the cohesion at will is a necessary condition to develop a fundamental understanding of the flow of cohesive materials and powders. In our group we have recently developed a technics to coat silica particles with polymers and we are able by controlling the coating thickness to continuously varies the cohesion properties, and goes from a cohesionless to a highly cohesive medium. The proposed project consists in using this material to investigate the packaging process. We will first study the rheology of the model material, before analysing a simplified version of a packaging process. We should be able to investigate the role of cohesion and of the rheology of the material in the different steps of the process, from the flow in the hopper to the formation of the deposit, looking also at the stability of the final packing to tap perturbations.

A. General context and state of art

Powders are omnipresent in many industrial processes but predicting their behavior still represents a challenge (Schulze 2008). Whereas the description of coarse granular media has notably progressed during the last 20 Years (Andreotti et al. 2013), our understanding of the physical mechanisms involved during powder flow remains sparse, which represents a real challenge both for engineers designing new industrial processes and for physicists seeking for a unified framework to predict particulate flows. The difficulty comes from the presence of adhesion forces between the grains at the origin of problems of clogging, flow heterogeneities, agglomeration, intermittent flows encountered during the storage, the transportation, the processing of the material. No unified framework exists that can predict and describe the rich variety of behaviors observed with powders, and industry relies on empirical characterization to measure the so-called "flowability", the ability of powders to flow (Castellanos 2005; Tay et al. 2016). This concept that lacks solid physical bases, consists in estimating different properties (compaction, heap angles . . .) mostly related to static properties. Recently, powder rheometers have been developed based on the measurement of the torque experienced by a helix rotating in the powder (Hare et al. 2015). All these measurements are of crucial importance in many industrial processes, but do not not have a predictive power, and no framework is nowadays relevant to describe and capture the complex properties of cohesive granular media. Understanding the concept of ”flowability” from a physical point of view is still a challenge.

The challenge posed by IFPRI in this call concerns the aeration and deaeration of fine particles encountered when handling powders and particularly during the filling and packaging process (Rathbone et al. 1987). The control and the reproducibility of the filling process pose major problems such as intermittent flow rates, air trapping, intempestive recompaction of the material during manipulation. Despite the apparent simplicity of the configuration of filling a bag with powders, the process involves different physical phenomena, from the rheology of powders to two-phase flow when the interaction between the powder and the air is important. To improve our fundamental understanding of the mechanics controlling the packaging processes, I think three main questions need to be addressed: the role of particle properties and of the rheology of the powder, the role of the feeding process, and the role of air.

The rheology of powder flows

The first and perhaps most important question concerns the role of the grain properties on the flow characteristics and in particular understanding the crucial role of the adhesion forces. Characterising the rheology of powders and its links to the grain properties is to my opinion a necessary step to progress in our understanding of the aeration problem. We need a detailed knowledge of the powders rheology in the regime encountered during packaging, which is a regime where the material is dense but flow rapidly under low level of stress, typically its own weight. This is a regime not captured by the classical characterisation of quasi-static properties of powders as measured in a Schulze’s shear cell, and there is a need for a controlled and relevant rheological protocol to characterize the "fluid regime". This question is currently motivating numbers of fundamental studies in the granular community (Vo et al. 2020). In absence of adhesion between particles, i.e for dry granular material made of grains interacting through frictional contacts only, a lot of progresses have been achieved. A key property of these materials is that in the limit of rigid particles, no internal stress scale exists in the system. This dimensional argument fully constrains the constitutive relations, leading to the writing of a rheology in terms of a friction law, relating the shear stress to the pressure through a macroscopic friction coefficient function of a single dimensional number called the inertial number I (Jop et al. 2006). This approach and its tensorial extension predict flows in many configurations like silo, avalanches, drums,..and can be enriched to capture transient effects due to dilatancy. One would like to get the same level of description with powders. However, adding adhesion between the grains dramatically changes the problem, as it introduces a new internal force scale, which modifies the scaling laws.

Recent numerical studies based on DEM simulations have shown that in presence of adhesion, the same framework might be relevant, but that a new dimensionless parameter has to be taken into account in addition to the inertial number to describe the rheology (Rognon et al. 2008; Vo et al. 2020). This number called the cohesion number measures the relative importance of adhesion and confining forces. Numerically, we have recently shown in my group that the story is more complex, that other parameters like stiffness and dissipation play also a crucial role when adhesion is present (Mandal et al. 2020), and that the rheological laws are non monotonic, leading to shear banding (Mandal et al. 2021) and instabilities that may be crucial to understand the concept of "fluidity". These results open new ideas to try do describe from a continuum perspective the flow of powders, and any advance in this direction will help in better understand the dynamics observed in packaging processes.

The role of the feeding technics

The second question of importance in the packaging process concerns the influence of the mode of supply. One would like to understand how powders flow from a hopper, on a chute, from a screw, how the flow characteristics change when changing the powders properties, and how the final deposit obtained in the container depends on the way the powder has been transported. This challenge, which is about to be achieved for simple granular materials are still fully open for cohesive materials, and there is a real need for controlled experiments in simplified flow configurations. One of the main question would be to understand to which extend the heterogeneities observed in the final bag are related to heterogeneities developing during the flow. Looking at the different instabilities that may arise in the different flow configurations is a way to improve our understanding of the origin of the variability in packaging processes.

The role of Air

Finally, a last crucial point for the dynamics at high flow rates and using fine particles concerns the coupling with air. Air might be entrained during the flow, and get trap in the deposit. It may then affect the structure of the deposit, and also can be a source of strong instabilities during the manipulation of the filled container. If mechanical perturbations of vibration are imposed, for exemple during transportation, the packing initially in a very loose state might be destabilized, and dramatic phenomena, including sudden fluidisation and compaction, may occur. This phenomenon similar to the well-know liquefaction in soil mechanics, is not really studied in details for powders, and a challenge would be to understand the role of the cohesion in this transient fluidisation process.

Our approach

The ambition of the CapCap Project is to study a simplified version of a packaging process on a model material, for which cohesion is controlled. We believe that being able to tune the cohesion at will is a necessary condition to develop a fundamental understanding of the flow of cohesive materials. We just develop in our group a method to coat in a control manner particles with polymers, a promising way to tune at will the adhesion. We should then be able to go from cohesionless particles to very cohesive material, and study how the rheology, the flow in a hopper and chute, and the resulting deposit in the bag varies with inter-particle adhesion.

B. Research Program

Ideally to understand the role particle interaction in the flow of cohesive materials, one would like to be able to experimentally tune the cohesion at will, in order to follow how the dynamics is modified when increasing gradually the inter-particle adhesion from the well known case of granular materials. Whereas in suspensions, playing with the chemical properties of the solvent is a way to change the interaction from repulsive to attractive (Van De Laar et al. 2016; Clavaud et al. 2017), for grains in air, the task is more difficult. Fundamental studies on cohesive granular media have then focused

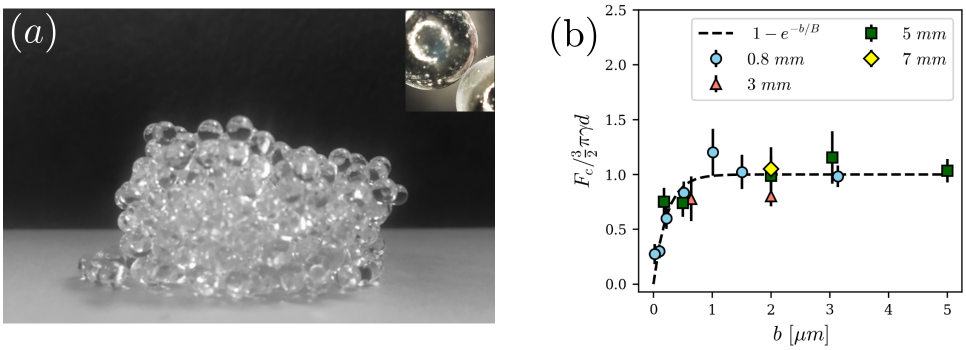

Figure 1: The model material: a) exemple of cluster formed by the coated particles b) rescaled interparticle adhesion force as a function of the averaged coating thickness.

on mixture of grains and liquid, in which cohesion is controlled by the amount of liquid through the formation of capillary bridges (Scheel et al. 2008). However, capillary bridges appear to migrate during flows, leading to strong heterogeneities (Badetti et al. 2018). Humid sand is thus of interest per se, but does not represent a model material to understand powders. Working with real powders is also a challenge as they are very sensitive to environment (humidity, temperature) preventing a precise characterization of their rheology. To circumvent this difficulty, we have recently developed in our group a simple method to introduce controlled adhesive forces between silica beads (Gans et al. 2020). The idea is inspired by the "kinetic sand", a toy for kids made of a mixture of sand and polymers which can be moulded and sculpted at will indefinitely. Our recipe is based on a mixture of PDMS, acid boric and water, mixed and heated with the particles during one hour. After cooking, the particles are coated with a layer of PolyBoroSiloxane (PBS), which makes them sticky (see Fig. 1a). The stickiness is stable, remains after many contacts, is present on every particle. The adhesion force is controlled by the thickness of the coating (see Fig. 1b). We have shown that this system is very stable in time, can be re-used with the same properties, making it an ideal material to study how adhesion may change the flowing properties of granular media, and thus a relevant model for powders. The research program proposes to use this new and unique model material to investigate how in the process of filling a container adhesion changes the dynamics and the deposit. Three main tasks are planned. First, the rheology of this model material will be analysed. Once the rheology characterized, we plan to study the flow in a simplified filling process consisting in emptying a silo in container. The aim is to understand how cohesion modifies the flow in the hopper, the heterogeneities at the exit, the formation and the structure of the resulting deposit. Finally the role of air will be studied in a second step using fine particles, with a focus on the stability of the packing submitted to tap perturbations.

Rheology of the model material

As a first task, we aim at characterizing the rheology of our model cohesive granular material. We will use the pressure imposed rheometer build in my group (Tapia et al. 2019) (Fig. 2a), where the grains are confined under a controlled pressure in an annular cell and sheared by a rotating top cover. The torque and position of the top plate provide accurate measurement for the shear stress and the volume fraction and thus a measure of the friction law and the volume fraction law. Our aim is to understand the role of the coating and how it changes the rheology under steady shear. The questions we would like to answer are : does adhesion induce a shear weakening branch in the friction law as observed in simulation (Mandal et al. 2021)? Can we put in evidence some scaling with adhesion as suggested in the literature (Vo et al. 2020) ? How transient flows starting from different controlled volume fraction are affected by adhesion and how it may affect dilatancy or compaction ? The results of the rheological study will serve as a base to analyse the flow characteristic in a filling process.

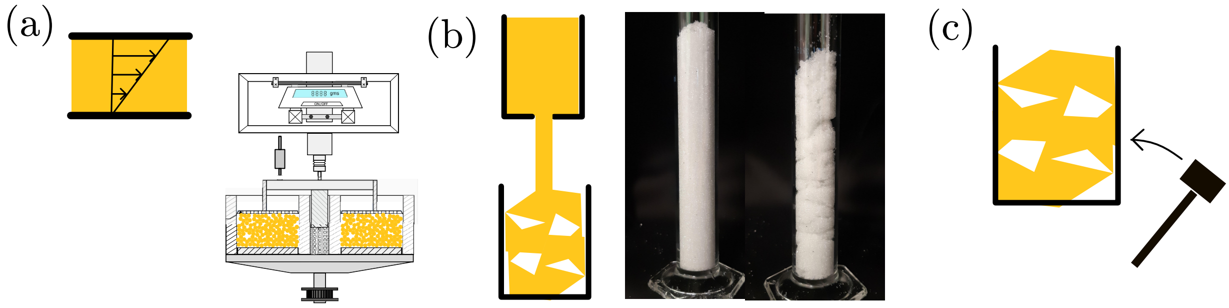

Figure 2: The three proposed tasks: a) Rheological characterisation of the model material; b) Studying a simplified feeling process (pictures show packings obtained for a low cohesion (left) and high cohesion(right) material; c) Compaction of a cohesive material.

Filling a container from a hopper

Once the rheology of the model cohesive material characterized, we plan to study the emptying of a silo in a container as sketched in Fig. 2b. The presence of cohesion is known to dramatically affect the flow in hopper, leading to channellisation and clogging (Schulze 2008). The ability to continuously modify the adhesion between the particles in our model material, gives us the opportunity to study and understand what controls the flow regime and when clogging appears. We will also carefully look at the heterogeneities that may appear at the exit of the hopper, to understand how cohesion affects the formation of clusters at the exit. Lastly we will study how the deposit is created from the flow. When preparing this proposal, we have conducted preliminary experiments to test the feasibility and check the interest of the proposed approach. Results of the filling of a tank is shown in Fig 2b for two different levels of cohesion. One clearly observes that the packing looks homogenous and dense when cohesion is low (left picture), whereas strong heterogeneities are observed at high level of cohesion (right picture), with the formation of clusters at the exit of the silo that keep their identity in the final deposit, trapping air. A detailed analyse of the formation of the deposit, of its structure (we have access in our university to an X-Ray microtomographe to measure the 3D structure of granular packing), of its stability during the feeling process should provide important information about the dynamics at work during the process and the role of cohesion.

Compaction of a cohesive material

The last task we would like to investigate in a longer term is the coupling of the packing with air. In the limit of very cohesive materials, the packing resulting from the emptying of the hopper is very loose. A perturbation, a shock or a vibration might destabilize the deposit and compact it. During compaction, the trapped air escapes. If the particles are coarse, air flows easily through the pores and the dynamics of compaction is simply controlled by the inertia of the particles. When the grains are fine, the air flow induces additional stresses due to viscous drag, which fluidizes the powder. This phenomenon called liquefaction when the fluid is water has been intensively studied in soil mechanics community. We propose to try to understand the role of cohesion in the his transient fluidisation of powders, using our model material. Traina et al (Traina et al. 2013) have shown that tap experiments, which consists in imposing a sudden acceleration to the packing, is an interesting test to discriminate between different powders. With our new model material, playing with both the adhesion force between particles and the particle size, we should be able to disentangle the role of cohesion and the role of air in the compaction under tap, by performing controlled experiments measuring simultaneously compaction and evolution of the air pressure during the dynamics.

C. Expected achievements

This experimental project focus on the understanding of the role of cohesion in the packaging process. We hope to be able to improve our physical understanding of the flowability of cohesive granular materials, to evidence how inter-particle adhesion influences flow in a hopper and the formation of heterogeneous structures during the filling procedure. This experimental project is part of a wider project in our group, with also numerical and theoretical approaches on the powder rheology, with the ultimate goal being to be able to propose relevant continuum description of the flow of powders.

D. Risks and critical unknowns

One of the main unknown of this research program is the use of the model granular material. Our first studies have shown its potential in controlling cohesion, a key challenge to improve our understanding of cohesive granular media. However, the coating of the particles might introduce more complexity than expected, for example one risk being that it might introduce also lubrification effects. This will be checked in our rheological investigation. We are also currently investigated other ways of controlling particle properties in collaboration with chemists, based on the click chemistry technics, which alow to graft almost any kind of molecules at the interface of polymer particles.

E. The team

Our group in Marseille has a strong expertise in granular flows, suspensions and in the rheology of complex fluids. With Maxime Nicolas and Pascale Aussillous, both professors at Aix Marseille University, we started four years ago 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 in the aeration problem raised in the IFPRI call, 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.

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