PHYSICAL BEHAVIOURAL STUDY OF MODEL METALLIC POWDER

P. Adamiec, M. Nemoz-Gaillard, D. Lepetz, J.Ch. Bénézet

Abstract
The physical behaviour of metallic powders can be studied with two approaches: an approach based on the work of Carr, measuring the angle of slope and the bulk densities and an approach based on the work of Coulomb, measuring the angles of internal friction and cohesion.
In this paper, we shall underline both the relations that exist between the parameters of the powder (shape, size of balls) and the values of various characteristics of physical behaviour, and between the different measurements produced by the two approaches. The presence of these relationships is clearly shown by a statistical study of all the results. All these results can model the mechanical behaviour of metallic powders.
Keywords: powder, bulk density, angle of slope, angle of friction, Principal Component Analysis

INTRODUCTION

Many raw materials (metal, cereals, coal, minerals, etc.) are granular materials that need to be transported, processed, mixed or stored. From the flow of powder in a silo to avalanches in a pile of sand, the behaviour of granular media is still poorly understood to this day [1]. In the framework of this work, a "model" granular medium was chosen by considering populations of spherical particles consisting of glass balls. This spherical model is a commonly model in numerous fields including the powder metallurgy, ceramic, geologic, pharmaceutical [2-5]. In the first step, the physical properties (specific density, granulometry, morphology, etc.) of the five populations of balls were measured. The physical behaviour of these products was then studied in terms of two approaches:

- an approach based on the work of Carr, measuring the angle of slope and the bulk densities.
- an approach based on the work of Coulomb, measuring the angles of internal friction and the cohesion.

In this paper, we shall underline both relations that exist between the parameters of the powder (shape, size of balls) and the values of various characteristics of mechanical behaviour, and between the different measurements produced by the two approaches. The presence of these relationships is clearly shown by a statistical study of all the results. All these results can model the mechanical behaviour of metallic powders.

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MATERIALS AND METHODS

Materials

The products used were solid balls of silica glass. Five populations of balls were chosen. Their granulometric distributions are given in Fig.1. The granulometric spectra were measured by laser granulometry (COULTER LS230).

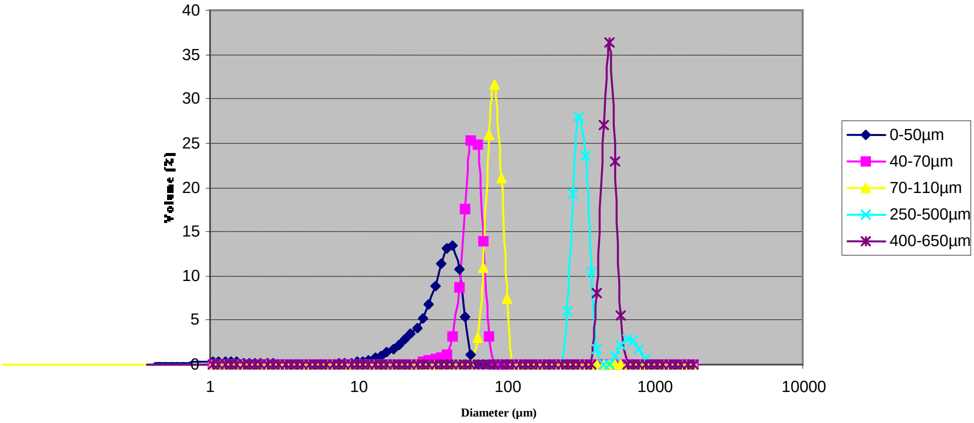

Fig.1. Granulometric spectra of the balls used.

Each granulometric spectrum was characterised by two values: the modal diameter (D_{mod}) and the granular distribution (D_{90}-D_{10}/D_{50}) (Table 1).

Tab.1. Granulometric characteristics of the ball populations.

Product	A	B	C	D	E
D_{mod} [µm]	46	60	88	324	517
D_{90}-D_{10}/D_{50}	0.87	0.38	0.30	0.32	0.26

The homogeneity of the morphology of the silica glass particles was verified by optical microscopy (Fig.2).

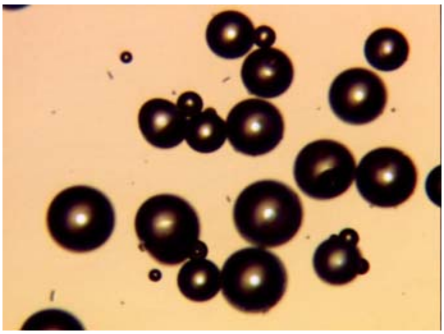

Fig.2. Morphology of the balls (B).

Methods

Two approaches were used in this study, and for each approach two types of measurements or experiments were carried out.

Measurement of bulk densities

The loose and tapped bulk densities were measured according to the protocol of Carr [6]. The tapped bulk density was measured after 180 taps using a HOSOKAWA brand instrument [7]. This property is calculated by measuring the mass of balls required to fill a container of a known volume.

Measurement of angles of slope

The angle of slope θ is measured from a pile obtained by allowing the material to flow through a vibrating screen then a funnel on a horizontal surface (Fig.3). The same instrument was used to carry out these experiments.

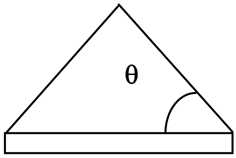

Fig.3. Diagram of the angle of slope.

Shear test: calculation of the internal angle of friction and cohesion

The standard method used to characterise the rupturing of solids, particularly soils, is the rupture criterion of COULOMB, which is expressed as follows (equation 1):

$$\tau \geq C + \sigma \operatorname{tg} \varphi \quad (1)$$

where **C** is the cohesion and φ the internal angle of friction.

In the case of powdered materials, Coulomb's criterion reduces to: $\tau \geq \sigma \operatorname{tg} \varphi$.

If σ and τ are the components of the stress acting on an element of the rupture surface and verify the Coulomb criterion, it is only necessary to measure two pairs of values of σ and τ to determine the mechanical rupture characteristics of the studied material.

The oldest instrument used to determine the rupture characteristics of soils is the box shear apparatus shown in Fig.4.

If P is the weight applied to the sample and F is the tangential force at a given instant (proving ring reading); assuming a uniform stress field in the sample, section S, we obtain equations (2) and (3):

$$\sigma = \frac{P}{S} \ (2) \text{ and } \tau = \frac{F}{S} \ (3)$$

With the stress σ maintained constant throughout the test, we can plot the curve representing the variation in the tangential force in function of the slip in the shear plane (Fig.5).

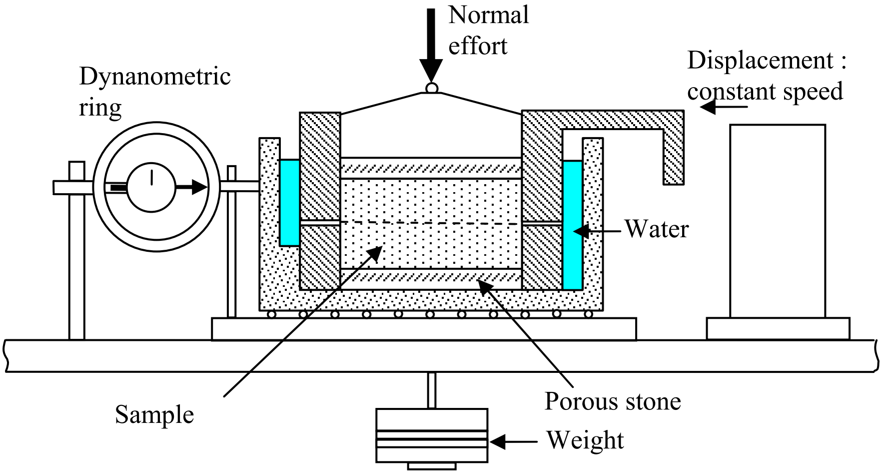

Fig.4. Working principles of the shear apparatus.

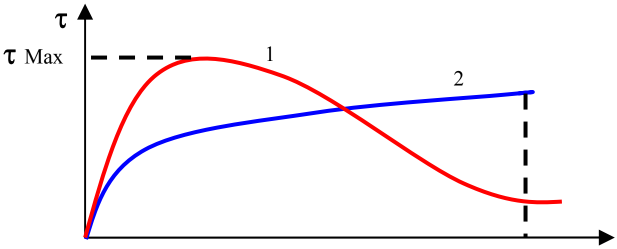

Fig.5. Rupture of the pile-up of divided solids.

δ

Curve 1 corresponds to the behaviour of closely packed fine sands or compacted clays. The rupture occurs suddenly (significant peak). Curve 2, on the other hand, corresponds to the behaviour of loose pile-ups and/or plastic products. The rupture is poorly characterised and also defined by a certain percentage of deformation.

For each test, a pair of values (σ_i, τ_i) is obtained, corresponding to a point on the intrinsic straight line (Figs.6 and 7).

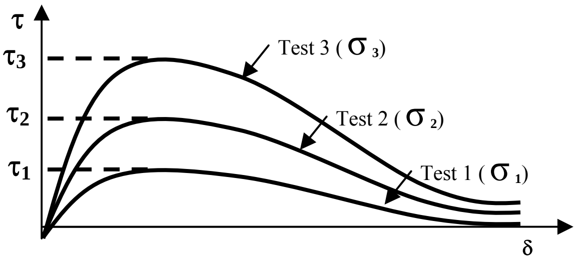

Fig.6. Shear curve of 3 samples of the same nature.

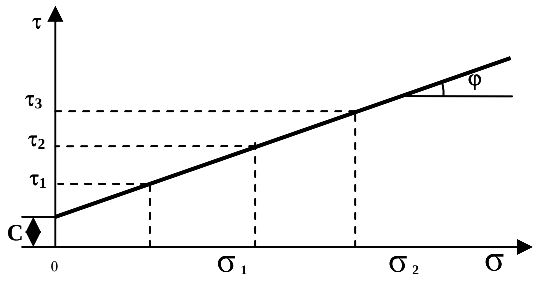

Fig.7. Plot of the intrinsic straight line.

For the five types of balls, three different trials were carried out, corresponding to three different normal stresses: 0.1 MPa, 0.2 MPa and 0.3 MPa. These trials were performed with the balls randomly distributed in the box.

RESULTS

Measurement of Bulk Densities

The various loose and tapped bulk densities are given in Table 2.

Tab.2. Bulk Densities.

Product	Diameter [μm]	Loose BD [g/cm^3]	Tapped BD [g/cm^3]
A	46	1.26	1.51
B	60	1.38	1.53
C	88	1.42	1.56
D	324	1.55	1.53
E	517	1.57	1.54

The results show that the loose bulk density is in function of the size of the balls. The tapped bulk density shows no clear evolution in values. This phenomenon may be explained by the ejection of balls during the operating protocol. For the measurements of tapped bulk densities, we consider that the value is stable in function of the number of taps and independent of the size of the balls [8].

Measurement of Angles of Slope

The measurements of the angles of slope are given in Table 3 and Fig.8.

Tab.3. Angles of Slope.

Product	A	B	C	D	E
Angle [°]	34	32	30	23	24

The measurement of the angle of slope shows that it also depends on the size of the balls. The ball populations fall into two granulometric domains: one domain for the balls less than 150 μm in size, for which an increase in size leads to a lower angle of slope, and a second domain for the balls larger than 150 μm, for which the angle of slope is constant and must depend only on the density of the balls.

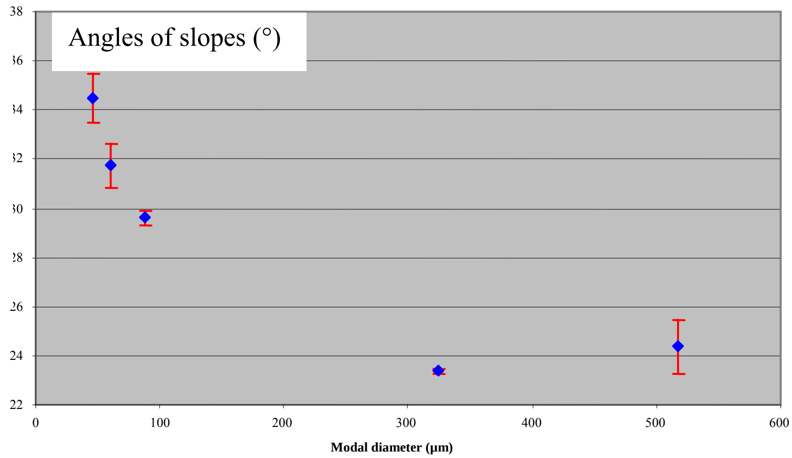

Fig.8. Angle of slope in function of the diameter of the balls.

Measurement of the Internal Angle of Friction and the Cohesion

The internal angle of friction and the cohesion were calculated using the shear curves (Table 4).

Tab.4. Values of the internal angle of friction and the cohesion.

Product	A	B	C	D	E
Angle φ [°]	32	30	31	24	26
Cohesion C [MPa]	0	0	0.007	0.006	0.001

Table 4 shows that the material is non-cohesive (glass). However, the values of the angle of friction evolve in function of the granulometry of the ball populations (Fig.9).

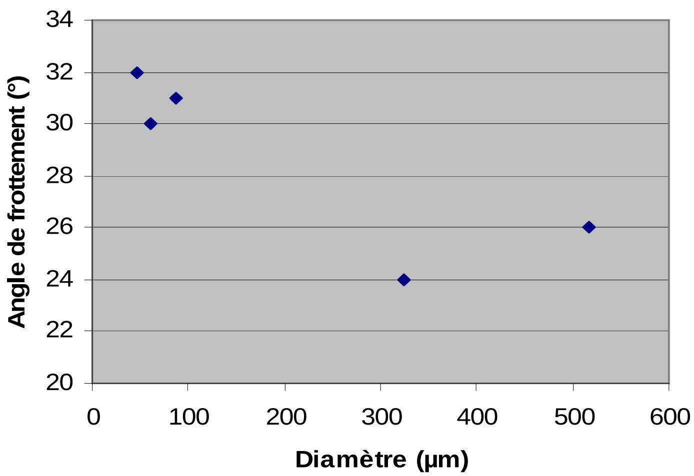

Fig.9. Internal angles of friction in function of the size of the balls.

The measurement of the internal angle of friction also shows a critical size at 150 µm, which differentiates the two domains of balls.

CARR AND COULOMB APPROACHES

Relation between internal angle of friction φ and angle of slope θ

The results of the measurements corresponding to the two approaches highlight a link between the angle of slope and the internal angle of friction (Fig.10).

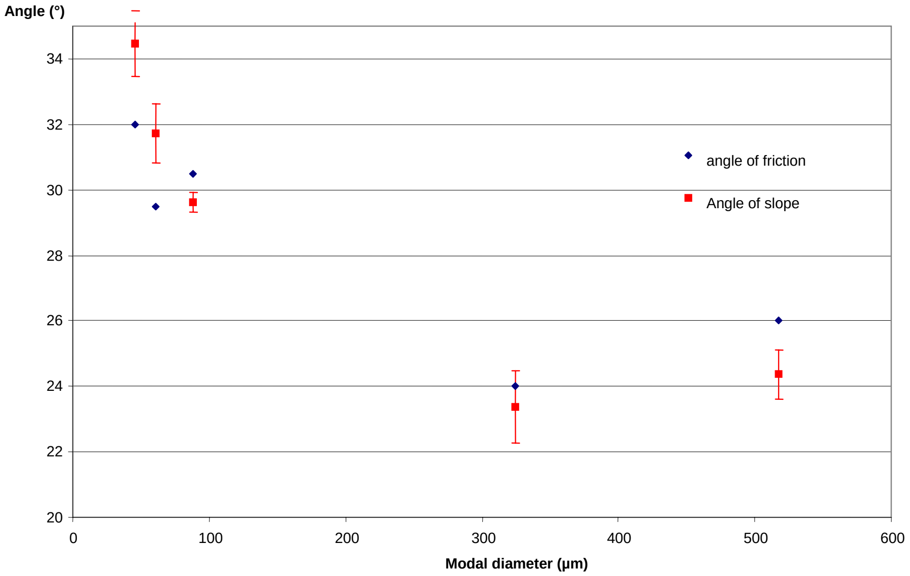

Fig.10. Internal angle of friction and angle of slope in function of the size of the balls.

Interpretation based on elementary treatments

To try to classify the behaviour of the powders, we carried out a Principal Component Analysis (PCA) on all the available data, i.e. the variables defined by: the granulometry, the angle of slope, the density, the angle of friction and the cohesion. These variables were measured for the different states (loose and tapped) of the powders, with each pair (powder diameter, state) representing an individual (Fig.11).

Concerning the individuals, the analysis showed a first principal axis whose contribution was 33%. Taking into account the experimental results, this axis shows a contract in behaviour between the powders whose granulometry is less than 100 µm and those whose granulometry is greater than 300 µm. The second axis does not show any particular separation between the individuals.

Concerning the variables, the first two principal axes of the analysis show a very significant contribution, more than 80% on average, whatever the set of variables used for the analysis.

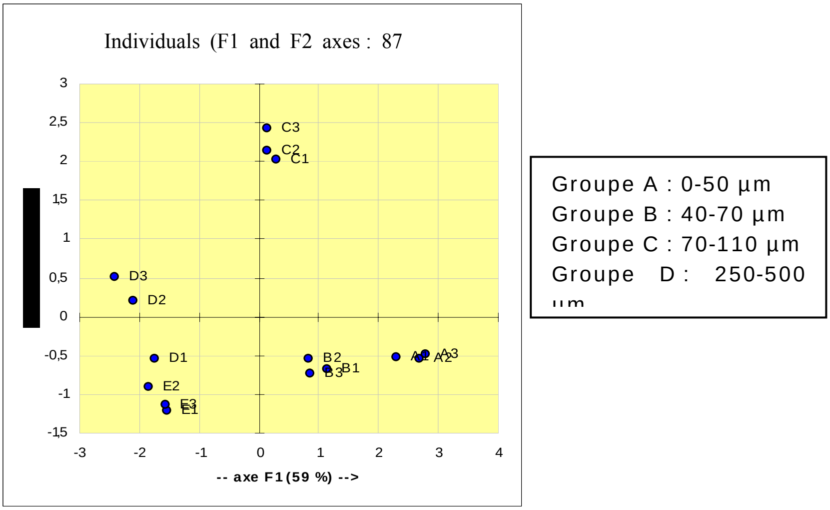

Fig.11. Coordinates of the individuals on the two principal factorial axes.

Analysis of the correlation circles (Fig.12) leads to the following observations:

- in all cases, the angle of slope and angle of friction are highly correlated, with the exception of the finest granulometry (0-50 µm powder); in particular, this correlation holds true whatever the normal strain of containment applied during the shear test,
- moreover, these two angles show a negative correlation with the density, whatever the state of the powder (loose or tapped),
- for all the circles, the angle of slope and angle of friction are positioned perpendicularly to the cohesion, indicating total independence between these variables.

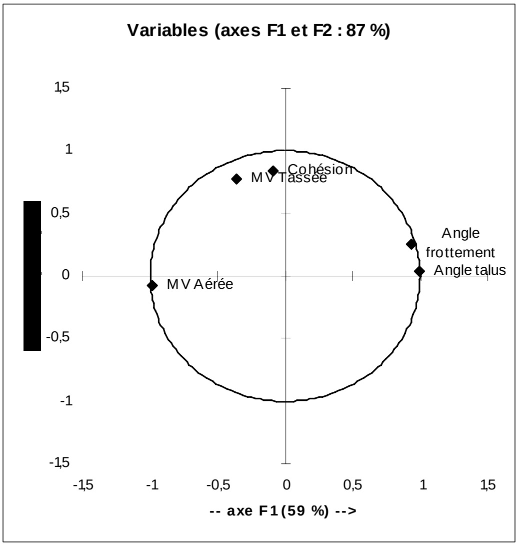

Fig.12. Coordinates of the variables on the factorial axes.

CONCLUSION

The results obtained by these two approaches enabled various physical characteristics to be compared with one another, and also highlighted relations between the mechanical behaviours of the ball populations and their physical characteristics. The results of this study confirmed the existence of a relationship between the angle of slope and the internal angle of friction [9]. The size of the particles plays a determining role in the mechanical behaviour of dry granular media [10]. The results seem to show different physico-mechanical behaviours for balls A, B and C, on the one hand, and D and E on the other. The diameter between the two zones is situated at 150 µm in the case of glass balls.

All the experimental results were analysed statistically. This analysis also showed a separation between the clouds of individuals situated on either side of the "critical" diameter. For balls A, B and C, the clouds are distinct, whereas for balls D and E they are disparate. There is no further difference in behaviour beyond a certain diameter.

The various behaviours of the products can be explained by the preferential assemblies of the particles. Nonetheless, there is currently a lack of metrological information concerning the granulometric range 100 to 300 µm. This lack of information needs to be filled in order to confirm the existence of the apparent "critical" zone at 150 µm. In addition, the study could be complemented by using balls of diameter greater than 500 µm.

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