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Characterisation of flow properties of *foutou* and *foufou* flours, staple foods in West Africa, using the FT4 powder rheometer

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Abstract Flowability and fluidisation of plantain-based flours from three varieties (Orishele, Corne 1, and French 2) were assessed using FT4 powder rheometer. Studied powders exhibited good flowing and fluidisation properties with little differences attributable to variety type. *Foutou* flours constituted by larger particles with a low proportion of fine particles were more compressible than *foufou* flours. *Foufou* flour of Orishele had the better flowability and was the most fluidisable because of its high content in large particles of relatively convex and angular shape. *Foutou* flour of Corne 1, containing more small particles, was slightly less flowing and fluidisable than other flours.

Keywords *Foutou* · *Foufou* · Powder · Plantain variety · Flowability · Fluidisability

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Introduction

Food shortage in sub-Saharan Africa mostly results from high post-harvest losses of agricultural products caused by poor harvesting techniques, presence of parasites and pests, poor access to major production centres, storage issues, low processing level of agricultural products, and weakness of agricultural production. Several solutions exist to reduce post-harvest losses, among which fruit transformation into less perishable products (flour, chips, etc.) is clearly the most concrete, especially as far as trading is concerned [1].

In Côte d'Ivoire, plantain is the third basic foodstuff after yams and cassava [2] and it is the main consumed food in producing regions. Plantain is prepared in diverse forms like *foutou* and *foufou*, highly cherished dough-like foods. *Foutou* is obtained by cooking peeled plantain fingers and cassava roots and pounding them in a mortar, whereas *foufou* is prepared by cooking peeled plantain fingers and crushing them in a mortar, then adding palm oil. Small balls of these pastes are manually rolled by the consumer and eaten with traditional sauces, together with meat, fish, or vegetables. The consumption of *foutou* and *foufou* remains limited because preparation is tedious and time-consuming.

Foutou flour was developed in several countries of West Africa like Ghana and Côte d'Ivoire by mixing plantain and cassava flours with starch [3]. The production of plantain flour and its suitability for preparing reconstituted *foutou* or *foufou* with a satisfactory texture might be limited by browning reactions and degree of plantain ripeness. Unpublished recent studies conducted by the authors of the present manuscript showed through sensory analyses that Ivorian consumers prefer flours prepared with semiripe plantain pulp. The production of these flours at industrial scale could significantly increase plantain productivity and

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farmer incomes, improve their living conditions, and contribute to food security of populations.

The flowability of food powders is important in handling and processing operations, such as storage and flowing in hoppers and silos, conveying, formulation, mixing, and packaging [4, 5]. The control of powder flow properties will allow increasing production efficiency and improving product quality. The FT4 powder rheometer (Freeman Technology) provides comprehensive series of methods that allow powder behaviour to be characterised across a whole range of process conditions. Specific energy (SE), extracted from the results of dynamic (stability and variable flow rate) tests, correlates well with the flow performance of a powder in a low stress environment (for instance, powders being fed gravimetrically, like in die filling operations). Basic flowability energy (BFE) is very useful for measuring the effect of many variables, such as amount of flow additive, moisture content, milling influence, end point of granulation, etc. The aeration test is likely to provide useful information for pouring operations and processing in fluidised beds. Compressibility test is indicative of the potential of flours to pack down during storage in big bags. Permeability is of interest when trying to understand the effects of several process environments such as storage, filling, fluidisation, etc. Last, shear cell measurements are widely used to assess the flowability of powders in high-stress conditions, such as processes involving powder discharge. These tests were originally used to design hoppers and silos, but have become increasingly useful for general characterisation of granular materials [6, 7].

The objective of this study was to characterise flow properties of *foutou* and *foufou* flours obtained from different plantain varieties in order to predict powder behaviour under different stress conditions.

Material and methods

Material

Foutou and *foufou* flours were produced from plantain pulp of Corne 1 (False Horn), French 2 (French), and Orishele (False Horn) varieties at stage 5 of ripening, i.e. more yellow than green [8, 9]. Plantains were grown in a farm located in Azaguié at 50 km east of Abidjan. They were all harvested at a stage of maximal maturity (stage 1 of ripening), i.e. when at least one ripe fruit appeared on the bunch [10], and ripened artificially up to stage 5 by using a solution composed of 20:80 (v/v) ethylene glycol:deionised water [11]. Fresh cassava roots of Bonoua variety were purchased at the wholesale market of Port-Bouet (Abidjan, Côte d'Ivoire).

Based on sensory analyses (data not shown), the convenient *foutou* flour was obtained by mixing dried plantain and cassava flakes with cassava starch in suitable weight proportions (70:20:10 w/w/w) and grinding the mix successively in two hammer mills. The first grinder (I2T, Abidjan, Côte d'Ivoire) was equipped with a 500 µm sieve and the second grinder (Forplex, Béthune, France) was supplied with a 200 µm sieve. Then, flours were packed in polyethylene bags placed inside Kraft bags to extend powder shelf life and prevent discoloration. For producing blanched plantain dried flakes, plantain fingers were blanched for 15 min in boiling water containing 0.5% (w/v) citric acid (Sigma–Aldrich), then peeled. After that, pulps were longitudinally cut in half and soaked during 15 min in a 1% (w/v) sodium metabisulphite (E223, Sigma–Aldrich) solution in order to limit enzymatic browning. Then, pulps were sliced into 10 mm cubes using a food slicing device (Vitalex, Cantanduva, Brazil) and dried in a mechanical dryer (MINERGY, ATIE PROCESS, France) at 65 °C for 8 h to reach between 8 and 10% (w/w) moisture content (on wet basis). Blanched cassava flour was obtained by blanching cassava slices for 10 min and drying them as described for plantain. Starch was isolated from cassava according to the procedure reported by Amani [12] with slight modifications. Cassava tubers were washed, peeled, and immediately cut into small slices that were crushed in a blender (Moulinex, Lyon, France). Obtained paste was mixed with water (1:5 (w/v)) and the obtained suspension was sieved at 100 µm (Retsch, Haan, Germany). Starch was finally recovered after decantation of sieved suspension. This process was repeated four times and recovered starch was dried in a ventilated oven (Memmert, Schwabach, Germany) at 45 °C for 48 h to reach about 8% (w/w) moisture content (on wet basis). The following notations were used in this study: FTOR, FTC1, and FTFR2 for *foutou* flours of Orishele, Corne 1, and French 2 varieties, respectively.

Foufou flour processing stages were close to those of *foutou*. In fact, after blanching, plantain pulps were cooked in a tampon solution containing 0.3% (w/v) sodium pyrophosphate (pH = 4.5), before being sliced, dried, and grinded in the same conditions as *foutou* flours. In this study, the notations FFOR, FFC1, and FFFR2 designate *foufou* flours of Orishele, Corne 1, and French 2 varieties, respectively.

Physical properties of foufou and foutou flours

Particle size distribution of *foufou* and *foutou* flours was measured using a laser granulometer Mastersizer 3000 (Malvern Instruments Ltd., Worcestershire, UK) supplied with the Aero S dry dispersion unit. Samples were analysed after air dispersion at 1 bar (100% air pressure, 40% feed rate, 2 mm hopper length). Particle size distributions were characterised by the mean particle size D_{50}, i.e. the granule diameter for which 50% of the volume of particles have lower diameters, and the span, describing the width of the distribution, calculated by the following formula: Span = $((D_{90} - D_{10})/D_{50})$. Mean sphericity and convexity of flour particles (evaluated at D_{50}) were analysed with the QICPIC high speed image analysis sensor (Sympatec GmbH, Clausthal-Zellerfeld, Germany) supplied with the LIXELL dispersion module following the procedure described by Gaiani et al. [13]. Particle microstructure was observed under a scanning electron microscope (S-240 Rustat Road, Cambridge, United Kingdom) operated at an accelerating voltage of 15 kV. Prior to analysis, samples were deposited on a carbon adhesive tab (EMS® 77825-12) at room temperature and coated with a mixture of gold and palladium for 100 s in a Polaron SC7640 sputter coater (Thermo VG Scientific, East Grinstead, England). Micrographs were acquired at ×250 magnification.

Flow properties of flour samples

Flow properties of studied *foutou* and *foufou* flours were measured using the FT4 powder rheometer that has previously been described in the literature [14]. Stability, compressibility, permeability, and rotational shear tests were performed with the standard methods of FT4. Aeration test was carried out with a modified method (air velocity ranging from 0 to 5 mm s^{-1}). To ensure analytical reproducibility, FT4 analyses include a preliminary step of powder conditioning, performed by a rotational and vertical moving both downward and upward of a blade (5° helix angle and 23.5 mm diameter) at constant speed of 60 mm s^{-1}. This operation removes any packing history such as pre-consolidation or excess entrapped air and generates a uniform powder packing in order to ensure repeatable and comparable data [6].

Stability

The stability test includes seven conditioning and test cycles. Detailed description of the stability test can be found elsewhere [7, 15]. Stability test cycles were realised by the rotating movement of the blade into and through a powder bed contained in the measurement cell (50 mm × 260 mL glass cylinder) at a tip speed of −100 mm s^{-1} and helix angle of −5°. During both downward and upward rotational movement of the blade, the torque (τ) and axial force (normal stress, σ) required to move the blade though the powder were recorded and used to calculate the total energy input required to make the powder bed flow. The most important parameters measured with the stability test are defined below.

Basic Flowability Energy (BFE) corresponds to the stabilised flow energy of test 7 that represents the energy needed to displace a conditioned powder sample during downwards moving of the blade (Eq. 1):

$$BFE = Flow\ energy\ of\ test\ 7 \tag{1}$$

Specific Energy (SE) is the energy needed to displace the conditioned powder bed during upwards testing divided by the mass of analysed powder sample. Unlike BFE, which is dependent from bulk compressibility, powder consolidation level, and density, SE mostly relates to intrinsic particle properties, such as cohesion, particle size and shape distributions, and surface roughness.

Aeration

The aeration test consists in the measurement of the reduction of powder flow energy when submitted to a gradual increase in air velocity. Aeration test has been described elsewhere [7, 15]. Powder sample was placed in the measurement cell (i.e. 50 mm × 260 mL glass cylinder) fitted with a porous plate. Prior to aeration test, three conditioning cycles were carried out to achieve a homogeneous reproducible initial state of powder bed. A complete test was then performed by measuring the flow energy of the powder bed at increasing air velocities from 0 to 5 mm s^{-1} by 0.5 mm s^{-1} steps. Between each aeration test cycle, a conditioning cycle was carried out to achieve a steady state of aerated powder. Flow energy was calculated from the energy required to move the blade downwards at −100 mm s^{-1} tip speed through the powder bed. Various aeration parameters were determined by the FT4 powder rheometer:

- The Aeration Energy (AE) is the flowability energy at maximal air velocity (5 mm s^{-1}).
- The Aeration Ratio (AR) designates the factor by which the basic flowability energy is reduced when aerating the powder bed at maximal air velocity of 5 mm s^{-1} (Eq. 2):

$$AR = \frac{Flowability\ energy\ at\ 0\ \mathrm{mm\ s^{-1}}\ air\ velocity}{Flowability\ energy\ at\ 5\ \mathrm{mm\ s^{-1}}\ air\ velocity} \tag{2}$$

- The Normalised Aeration Sensitivity (NAS) is a measure of powder sensitivity to aeration, especially at small air velocities. It is defined as the maximal difference in normalised test energy between the two consecutive points of the test, divided by the change in air velocity. Normalised total energy was calculated as the ratio between total energy at investigated air velocity and total energy in the absence of air flowing.

Another parameter, the minimum fluidisation velocity, was determined from aeration test results. It is the minimum air velocity needed to establish fluidisation in the powder bed. It was considered that fluidisation occurred when the flow energy was close to zero, i.e. inferior to 10 mJ in the conditions of the aeration test.

Compressibility

Compressibility is a measure of how powder density changes as a function of applied normal stress. Compressibility test has ever been described elsewhere [7, 15–17]. A sample was first placed in the measurement cell (i.e. two overlaid 50 mm × 85 mL glass cylinders) and submitted to three conditioning cycles. After that, the vessel was split to remove any excess powder and the dynamic blade was replaced by the 48 mm vented piston. Then, powder was slowly compressed by the vented piston moving vertically at 0.05 mm s^{-1} and applying levels of normal stress from 0.5 to 15 kPa while measuring the volume change. Afterwards, the compressibility (percentage change in volume after compression, % CPS) was plotted against the normal stress σ.

Permeability

Permeability is a measure of how easily the powder bed can transmit air through its bulk. Detailed description of the permeability test can be found elsewhere [7, 16]. The sample was placed in the measurement cell (i.e. two overlaid 50 mm × 85 mL glass cylinders) fitted with a porous plate and an air mass flow controller. Then, the powder bed was pre-conditioned in three conditioning cycles, vessel was split to remove any excess powder, dynamic blade was replaced by vented piston, and powder was compressed under increasing normal stresses from 1 to 15 kPa, while at the same time air was passed up through the vessel at a constant vertical velocity of 2 mm s^{-1}. The permeability of a powder bed was expressed as the pressure drop across the powder bed (PD) at 15 kPa applied normal stress.

Shear cell

Shear cell measurements are widely used to evaluate the flowability of powders in high-shear applications. The shear tests were carried out using the rotational shear cell accessory (i.e. two overlaid 50 mm × 85 mL glass cylinders) of the FT4 powder rheometer. Detailed description of the shear test can be found elsewhere [7, 15, 17–19]. The powder sample was first conditioned to achieve a homogeneous reproducible initial state and slowly pre-compacted under a normal stress of 9 kPa with a vented piston. Then, the vented piston was changed for the shear cell head and sample was re-compressed to remove any disturbances caused by the split and to ensure that the surface of the sample was properly consolidated. After this preconsolidation step, the sample was pre-sheared at 9 kPa to achieve a critically consolidated state. The normal stress σ was then lowered and the shear stress τ necessary to cause powder bed failure and initiate flow was measured. The pre-shear/shear sequence was repeated five times at decreasing normal stresses σ from 7 to 3 kPa by 1 kPa steps. The curve representing the evolution of τ as a function of σ is thus the so-called yield locus. Shear cell parameters, major principal stress (σ_1), unconfined yield stress (σ_c), cohesion (τ_c), and internal angle of friction (φ) were then determined by analysis of the Mohr circle.

Usually, the flowability index *ff*, defined as the ratio between major principal stress σ_1 and unconfined yield stress σ_c, is used to characterise flowability (Eq. 3):

$$ff = \frac{\sigma_c}{\sigma_1} \quad (3)$$

Powders were classified by Jenike [20] according to *ff* values as follows:

$ff < 1$ not flowing, $1 < ff < 2$ very cohesive, $2 < ff < 4$ cohesive, $4 < ff < 10$ easy-flowing, $10 < ff$ free-flowing.

In addition to the parameters derived from Mohr Circle analysis, the measured shear stresses for the highest and lowest applied stresses were also recorded.

Statistical analysis

The software used for statistical evaluation was Statistica V.8.05 (StatSoft Inc., Tulsa, Oklahoma, USA). Experiments were conducted in triplicate and reported values correspond to means ± standard deviations. Data were statistically analysed by one-way ANOVA and the means were separated by Tukey's HSD test at $p < 0.05$.

Results and discussion

Physical characteristics

The physical properties of *foutou* and *foufou* are shown in Table 1 and Fig. 1. *Foutou* flours displayed bimodal particle size distributions whereas *foutou* flours exhibited monomodal particle size distributions. The mean particle size of *foufou* flour was higher than that of *foutou* flour for the same variety. D_{50} of flour samples increased according to variety in the following order: Corne 1, French 2, and Orishele. Except for FTOR, *foutou* flours had significantly less spherical and convex particles than *foufou* flours. SEM analysis showed that the structure of *foutou* flour was heterogeneous with small spherical particles on the surface of large angular particles on one hand (white full arrows on Fig. 1) and aggregates of small spherical particles on the other hand (white dashed arrows on Fig. 1). On the contrary, *foufou* particles were more homogenous and exhibited regular angular shapes. These results confirmed the measures of particle shape (sphericity, convexity) that revealed the more irregular shape of *foutou* flour particles.

Powder flow properties

Stability

Mean BFE and SE values measured with the stability test are presented in Table 2. BFE and SE are key parameters to express powder flowability in low-stress environments. It is generally observed that powders exhibiting low BFE values have good flow properties and inversely, high BFE is often obtained for powders that flow poorly. However, it should be mentioned that the opposite can also be true. Both cases were observed in this study. Indeed, non-cohesive *foufou* flours constituted of large angular particles had higher BFE than *foutou* flours, paradoxically. High flow energy can be measured for non-cohesive powders when the powder bed is efficiently packed and little subjected to compression. In this case, a large fraction of powder bed volume is set in motion by the blade during analysis, leading to high values of flow energy [7]. Despite their relative high content in small particles, *foutou* flours had low BFE, showing good flow properties. Similar results were observed by Leturia et al. [15] for a mixture constituted of carbon black and metal oxides. Indeed, sample polydispersity may induce a kind of “ball-bearing effect”: the presence of small

Table 1 Mean particle size and shape of *foutou* and *foufou* flour samples

Flour sample	D_{50} (µm)	Span (−)	Sphericity (−)	Convexity (−)
FFOR	131.3 ± 2.1^{a}	2.30 ± 0.06^{b}	0.795 ± 0.009^{a}	0.877 ± 0.002^{a}
FFC1	75.6 ± 1.1^{d}	2.40 ± 0.03^{b}	$0.775 \pm 0.003^{b,c}$	0.857 ± 0.001^{b}
FFFR2	116.3 ± 3.0^{b}	2.08 ± 0.03^{c}	$0.789 \pm 0.008^{a,b}$	0.877 ± 0.003^{a}
FTOR	83.0 ± 0.9^{c}	2.40 ± 0.00^{b}	$0.787 \pm 0.003^{a,b}$	0.815 ± 0.002^{d}
FTC1	57.1 ± 3.7^{e}	2.46 ± 0.15^{b}	0.762 ± 0.001^{c}	0.833 ± 0.000^{c}
FTFR2	73.5 ± 1.2^{d}	2.76 ± 0.00^{a}	0.742 ± 0.000^{d}	0.835 ± 0.001^{c}

Mean values followed by the same superscripted letters in the same row are not significantly different at $p < 0.05$

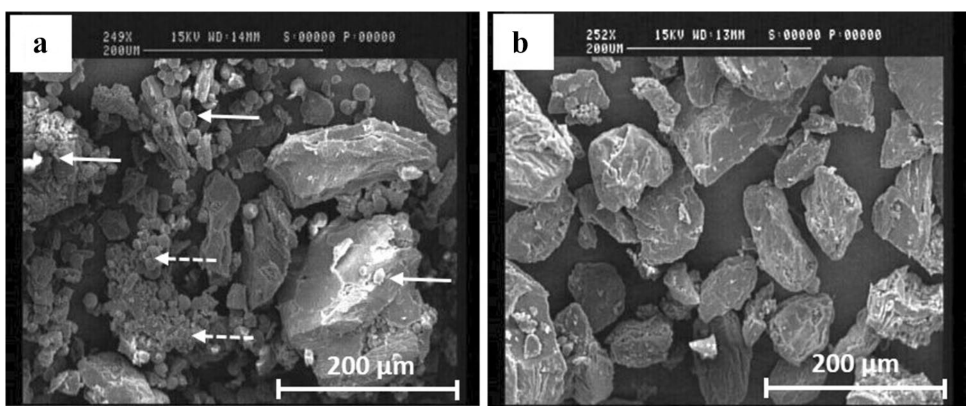

Fig. 1 Scanning electronic micrographs showing microstructure of **a** *foutou* and **b** *foufou* flours (×250 magnification). *White full arrows* show starch spherical granule stuck to the surface of large angular particles, whereas *white dashed arrows* point to agglomerates of small and spherical starch granules

Table 2 Stability and aeration test results

Flour sample	BFE (mJ)	SE (mJ g^{-1})	AE (mJ)	AR (−)	NAS (s mm^{-1})
FFOR	$1345^{a} \pm 28$	$4.36^{d} \pm 0.05$	$85.4^{b} \pm 12.7$	$24.2^{b} \pm 2.2$	$0.68^{e} \pm 0.01$
FFC1	$1274^{ab} \pm 72$	$4.25^{d} \pm 0.25$	$29.0^{c} \pm 3.6$	$72.6^{a} \pm 6.7$	$1.24^{c} \pm 0.02$
FFFR2	$1129^{c} \pm 35$	$4.91^{a} \pm 0.02$	$27.0^{c} \pm 1.6$	$81.1^{a} \pm 17.7$	$0.88^{d} \pm 0.03$
FTOR	$1017^{bc} \pm 58$	$4.74^{ab} \pm 0.11$	$198.0^{a} \pm 15.8$	$7.2^{b} \pm 0.7$	$1.41^{b} \pm 0.02$
FTC1	$865^{d} \pm 35$	$4.61^{bc} \pm 0.06$	$160.5^{a} \pm 22.6$	$7.4^{b} \pm 0.8$	$1.58^{a} \pm 0.01$
FTFR2	$901^{d} \pm 29$	$4.47^{cd} \pm 0.06$	$57.8^{bc} \pm 28.9$	$30.7^{b} \pm 0.11$	$1.38^{b} \pm 0.01$

Mean values followed by the same superscripted letters in the same row are not significantly different at $p < 0.05$

particles stuck at the surface of large particles (cf. Fig. 1) may reduce friction forces by decreasing the contact surface area, thus causing less resistance to flow and leading to low BFE values.

For all studied flours, SE were inferior to 5 mJ g^{-1}, indicating that *foufou* and *foutou* flours were not much cohesive. Excepted FFFR2, *foufou* flours had lower SE values than *foutou* flours, consistently with their larger mean particle size and lower cohesiveness.

Aeration

Aeration test data are presented in Fig. 2 and Table 2. All flours reached a fluidised state in the performed custom test. The minimum fluidisation velocity of *foutou* and *foufou* flours was of 1 and 1.5–2 mm s^{-1}, respectively. Both flour types were very sensitive to fluidisation but *foufou* flours needed slightly higher air velocities because of their higher content in large particles.

Significant differences in aeration behaviour were evidenced between all flour samples. Generally, the larger the aeration ratio AR and the lower the aerated energy AE, the less cohesive the powder. Following this rule, *foufou* flours were the more fluidisable (and probably less cohesive) powders. Moreover, the higher the normalised aeration sensitivity NAS, the more the powder is prone to aeration. *Foutou* flours presented lower NAS than *foufou* flours, confirming their higher aptitude to fluidisation. As explained by Freeman Technology, the more irregular shape of particles disrupted the air flow to a greater extent, resulting in turbulent flow and a large pressure differential across the particle, causing lift and suspension of the particles at relatively low air velocities. The low NAS value obtained for FFOR may be justified by its higher proportion of large particles of regular shape, which are more difficult to suspend in air than non-cohesive small particles of regular shape.

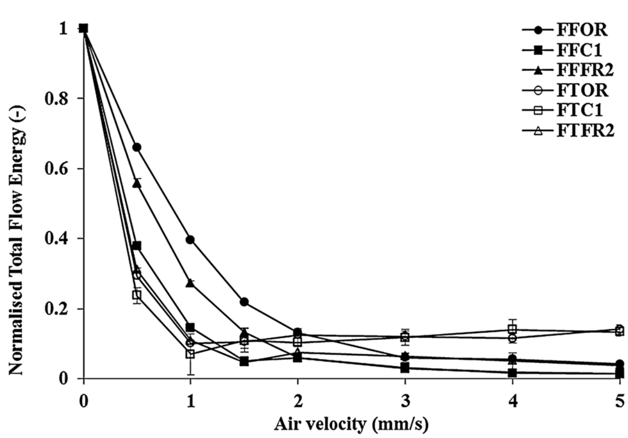

Fig. 2 Normalised total flow energies of *foufou* and *foutou* flours at different air velocities ranging between 0 and 5 mm s^{-1}. *Error bars* represent standard deviations; some were smaller than the marker size and thus not visible

Compressibility

As shown in Fig. 3, when increasing normal stress from 1 to 15 kPa, compressibility increased from about 1–2% to about 5–8% and 10–13% for *foufou* and *foutou* flours, respectively.

Significant differences were observed between compressibility results of flour samples (cf. Table 3). At 15 kPa, CPS values were relatively low for all studied flours, denoting a slightly compressible behaviour and therefore rather a good flowability. However, CPS values of *foutou* flours were about the double of those of *foufou* flours, indicating that *foufou* flours may have better flow properties than *foutou* flours. This difference in powder compressibility may be caused by particle size and shape. The compressibility of *foutou* flours was enhanced by the addition of fine cohesive cassava starch particles ($D_{50} = 13.7$ µm), acting as lubricating agent between large particles, inducing a "ball-bearing effect". This result is in agreement with those obtained by Leturia et al. [15]. FTC1 had a relatively higher CPS than other *foutou* flours. This may be due to its smaller particles of more irregular shape (cf. Table 1). Indeed, highly compressible powders entrain more air, and powders with a higher fine particle content and irregular morphology are likely to be more susceptible to compression than more spherical, larger particles. Also, FFC1 had relatively higher CPS value than other *foufou* flours because of its lower content in large particles.

Permeability

Figure 4 shows the pressure drop across the powder bed at 2 mm s^{-1} air flow for various applied normal stresses. Compression had little or no effect on permeability of studied powders. Pressure drop across *foufou* and *foutou* powder beds reached intermediate values, which is consistent with their moderate D_{50} values: investigated powders were not mostly composed of fine or large particles, which would have resulted in very low or very high permeability values, respectively.

Table 3 shows that *foutou* flours led to higher pressure drops PD, as they were less permeable than *foufou* flours. This was expected owing to the presence of fine cassava starch particles in small proportion in *foutou* flours, making the powder bed more compact and compressible than for *foufou* flours. Powders constituted of both large and fine particles may form more tightly packed powder beds, as fines are susceptible to fill the spaces between large particles, thus making the powder bed less permeable. This

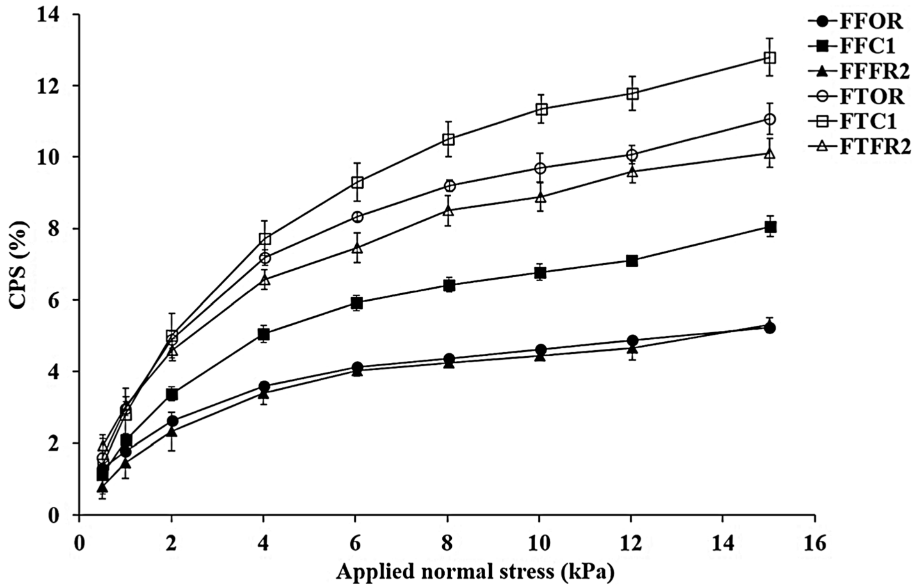

Fig. 3 Compressibility of *foufou* and *foutou* flours at normal stresses ranging from 0.5 to 15 kPa. *Error bars* represent standard deviations; some were smaller than the marker size and thus not visible

Table 3 Bulk properties and flow parameters deduced from compressibility, permeability, and shear tests

	FFOR	FFC1	FFFR2	FTOR	FTC1	FTFR2
CPS at 15 kPa normal stress (%)	$5.23^{d} \pm 0.01$	$8.05^{c} \pm 0.76$	$5.15^{a} \pm 0.07$	$10.74^{b} \pm 0.06$	$13.10^{a} \pm 0.16$	$9.72^{b} \pm 0.07$
PD at 15 kPa normal stress (mbar)	$4.76^{f} \pm 0.01$	$11.66^{d} \pm 0.02$	$5.72^{e} \pm 0.08$	$19.38^{b} \pm 0.09$	$30.11^{a} \pm 0.45$	$14.17^{e} \pm 0.28$
Cohesion, τ_c (kPa)	$0.10^{d} \pm 0.00$	$0.28^{e} \pm 0.01$	$0.23^{e} \pm 0.00$	$0.42^{b} \pm 0.02$	$0.72^{a} \pm 0.05$	$0.38^{b} \pm 0.00$
Flowability index, *ff* (−)	$40.2^{a} \pm 0.0$	$15.3^{e} \pm 0.6$	$18.5^{b} \pm 0.2$	$10.3^{d} \pm 0.4$	$6.1^{e} \pm 0.4$	$11.5^{d} \pm 0.2$
Shear stress at 3 kPa normal stress (kPa)	$1.79^{c} \pm 0.08$	$1.94^{bc} \pm 0.04$	$1.77^{e} \pm 0.03$	$2.00^{b} \pm 0.01$	$2.28^{a} \pm 0.05$	$1.82^{e} \pm 0.01$
Shear stress at 9 kPa normal stress (kPa)	$4.71^{ab} \pm 0.25$	$4.74^{ab} \pm 0.07$	$4.49^{b} \pm 0.04$	$4.74^{ab} \pm 0.02$	$5.13^{a} \pm 0.09$	$4.42^{b} \pm 0.00$

Mean values followed by the same superscripted letters in the same line were not significantly different at $p < 0.05$

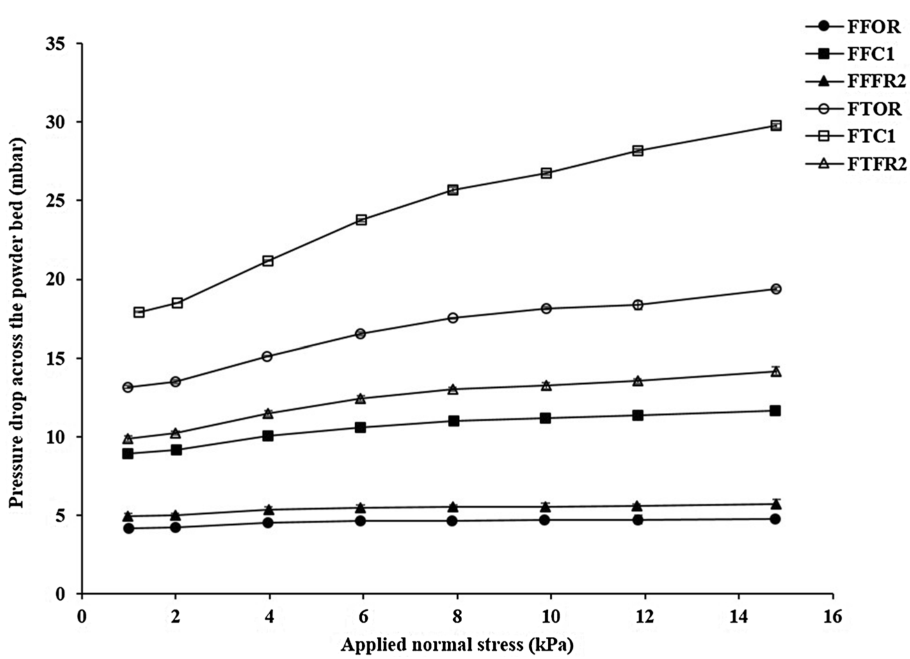

Fig. 4 Pressure drop through the powder bed at constant air velocity of 2 mm s^{-1} at different applied normal stresses for *foufou* and *foutou* flours. *Error bars* represent standard deviations; some were smaller than the marker size and thus not visible

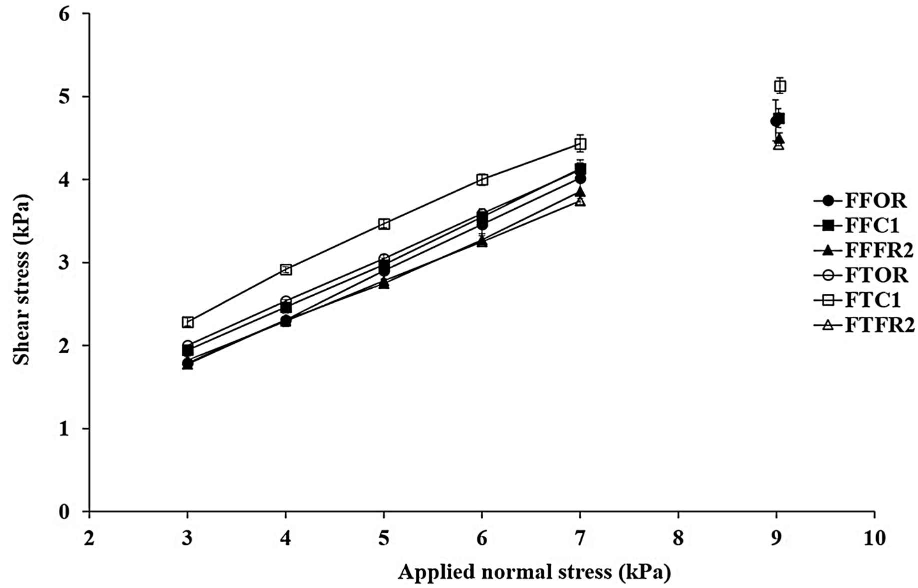

Fig. 5 Shear test yield logi of *foufou* and *foutou* flours after preshear at 9 kPa normal stress. *Error bars* represent standard deviations; some were smaller than the marker size and thus not visible

heterogeneity of particle size distribution was confirmed by SEM analysis (cf. Fig. 1). A similar trend was obtained by Jezerska et al. [21] working on titanium dioxide powders. As expected, the higher the powder compressibility, the poorer its permeability. FTC1 was the less permeable of all investigated flours and FFC1 the least permeable of *foufou* flours, because the flours prepared with Corne 1 variety contained smaller particles than other flours.

Shear test

The yield loci of *foutou* and *foufou* flours obtained after pre-shearing at 9 kPa normal stress are shown in Fig. 5. For all powders, shear stress increased with increasing consolidation stress.

Shear test parameters are presented in Table 3. All powders exhibited low cohesion values ranging from 0.10 to 0.72 kPa. In general, *foutou* flours were significantly more cohesive than *foufou* flours. Shear and compressibility test results were in good agreement: the higher the powder cohesion, the more compressible the powder bed. *ff* values were comprised between 6.1 (FTC1) and 40.2 (FFOR). *Foufou* and *foutou* flours were free-flowing, except FTC1 that was easy-flowing only: indeed, this sample had the highest cohesion value and was relatively more compressible than other flours. FFOR was the most free-flowing, owing to its higher mean particle size and lower particle cohesion in comparison with other flours. These results were in accordance with stability results that showed the good flowability of *foutou* and *foufou* flours. Studied powders had similar flow properties to industrial powders such as spray-dried, sieved, or coarsely milled lactose [7]. In general, particle size strongly affects powder sensitivity to cohesion [22–24]: powder cohesion generally increases when particles are smaller, which contributes to the poorer flow properties of fine powders.

The higher shear stresses at 3 kPa (2.3 kPa) and 9 kPa (5.1 kPa) were recorded for FTC1, confirming other shear cell results. This permits to state that in our case, the FT4 shear cell test was suitable for obtaining a classification of studied powders on the basis of their flowability.

Conclusion

The flow properties of *foutou* and *foufou* flours were investigated. The results showed the great influence of particle size distribution and particle shape on flow properties of *foutou* and *foufou* flours. All flour samples had good flowability properties and were easily fluidisable. However, *foutou* flours were slightly more compressible and less permeable than *foufou* flours, as the latter contained a lower proportion of fine particles. *Foutou* and *foufou* prepared from Orishele plantain variety had the better flow properties. This flowability information is useful for industrial processing, packing, and storage of *foutou* and *foufou* flours, as well as consumer handling. Therefore, in order to help mechanising and industrialising *foufou* and *foutou* production in sub-Saharan Africa, further investigations should focus on thermal, nutritional, and functional (rehydration ability, bioactivity, etc.) properties of these flours.

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