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Microstructure and physico-chemical bases of textural quality of yam products

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ABSTRACT

The texture of pounded yam is the main attribute of this traditional dish, one of the preferred ways of consuming yam in West Africa. We integrated functional properties and cell microstructure to describe or predict the textural quality of pounded yam. The firmness and adhesiveness of pounded yam prepared from six cultivars were measured. In parallel, the thermo-mechanical properties (DMA, DSC) and starch behaviour were also determined while the structure of raw, cooked and pounded yam was observed using Scanning Electron Microscopy, Light Microscopy and Confocal Laser Scanning Microscopy. No significant correlation was found linking DMA, DSC measurements with the textural quality of pounded yam (adhesiveness, firmness). Conversely, multiple regressions showed that 75% of the variation in firmness could be explained by the dry matter, soluble starch and amylose content of the pounded yam. In addition, CLSM revealed a thicker cell wall in Florido, a cultivar known for its bad pounding ability. We hypothesize that pectin, the major component of cell wall middle lamella, plays a role in the textural quality of pounded yam.

1. Introduction

Yam (*Dioscorea* spp.) is extensively grown in West Africa, where it is a major staple food and an important source of energy and other nutrients for the indigenous populations of Nigeria, Ghana, Benin, Côte d'Ivoire and Togo (Degras, 1986). Various types of edible yam (e.g. white yam, yellow yam, water yam) are grown in this region, which is known as the "yam belt", and some varieties are prestigious because of the high quality food dishes they provide (Dansi, 2001; Hounhouigan, Kayode, Bricas, & Nago, 2003), particularly pounded yam (Omonigho & Ikenebomeh, 2000). Pounded yam is obtained by cooking and pounding yam pieces for a better "feel" of the food in the hand and ease of swallowing (Omonigho & Ikenebomeh, 2000). Observations by processors have shown that preferred varieties have the ability to form mealy, elastic and smooth dough, while other varieties have a granular, non-homogeneous dough texture (Hounhouigan et al., 2003). Sensorial analyses confirmed that the ease of moulding and the springiness of the mass were the main positive attributes of pounded yam, whereas lumpiness (lack of smoothness) was the main reason for aversion (Akissoe, Mestres, Hounhouigan, & Nago, 2008; Nindjin et al., 2006). Recently, it was reported that the elasticity of pounded yam was linked to the dry matter content of the yam tuber (Akissoe et al., 2008).

In the traditional method of preparing pounded yam, yam pieces are first cooked in boiling water. The extent of cooking is regularly checked by prodding the yam pieces with the fingers or a fork to evaluate the ease of disintegration (a mealy texture is required). According to processors, friability/mealiness of cooked yam pieces is an indicator of poundability. Indeed *Dioscorea alata* tubers are generally less friable (Egesi, Asiedu, Egunjobi, & Bokanga, 2003), but no close relationship between friability and poundability has yet been evidenced. After pounding, the resulting dough is a composite material of 21–25 g/100 g dry matter content (wet basis) (Akissoe et al., 2008) made of nearly broken cells embedded in a starchy matrix (Brunnschweiler, Mang, Farah, Escher, & Conde-Petit, 2006). The extent of cell disintegration appears to be linked to the firmness of pounded yam, and is greater in *D. alata.* Unlike mealy cultivars, *D. alata* cultivars, which have a waxy texture, do not display cell separation after boiling (Otegbayo, Aina, Asiedu, & Bokanga, 2005). In the case of the potato, it has been established that texture is based on cell structure (cell walls and middle lamella) and starch content, which are important parameters for distinguishing firm and mealy potato cultivars (van Marle, Clerkx, & Boekestein, 1992). Martens and Thybo (2000) recently showed that certain structural features of cooked potato (such as the volume of the fraction of gelatinized starch, volume of the fraction of cell

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walls) were positively correlated with sensory properties (mealiness, graininess, adhesiveness and chewiness) of boiled potato, but poorly correlated with measurements of instrumental texture (fracture stress and strain). Physico-chemical measurements and starch functional properties alone cannot explain the sensory perception of the textural quality of cooked pounded yam. In this study, we thus combined the evaluation of functional properties and of cell microstructure to explain the textural quality of pounded yam. In addition, physical and textural properties were monitored during cooking to assess whether the mechanical properties of cooked yam (mealiness) are related to its poundability.

2. Material and methods

2.1. Plant material

Yam cultivars *Dioscorea rotundata* (Laboco, Gnidou, Morokoro, Anago and Kokoro) and *D. alata* (Florido) were obtained from farmers (Benin). The dirt was removed from the freshly harvested tubers which were transported to France by air freight one week later. The yams were stored for several months (4–8), without any anti-sprouting agents, in an air conditioned room (21 °C and 65% relative humidity).

2.2. Dynamic mechanical thermal analysis (DMA)

The flexural modulus was determined on yam pieces during cooking using the DMA 7e Dynamic Mechanical Analyzer (Perkin Elmer, Norwalk, USA) equipped with the stainless-steel 3-point bending measuring system with a 10 mm bending platform. Before running the experiments, the apparatus was calibrated using Indium in particular for temperature calibration.

After discarding 30 mm from the distal and proximate parts, the tubers were cut into five sections (30 mm in height) from the tail to head. Each section was cut into four quarters. Parallelepipedic yam pieces of about 6 mm (width) × 6 mm (height) × 10 mm (length) were carefully cut out from each quarter using a razor blade. The width and height were measured with a micrometer gauge. The sample was then covered with paraffin oil to limit water desorption during measurement. It was then placed on the platform and a static force of 30 mN was applied with an additional dynamic force of 20 mN at a frequency of 1 Hz. A temperature scan programme starting at 25 °C and increasing to 95 °C at 5 °C/min and holding for 3 min at 95 °C was applied. The storage (E') and loss moduli (E'') were calculated throughout the run, together with the ratio E''/E' referred as tan δ (Fig. 1).

2.3. Differential scanning calorimetry (DSC)

In parallel with DMA, thermal transitions were measured using a Perkin Elmer DSC7 analyzer. From each quarter analyzed by DMA, a small cylinder of 5 mm in diameter and 5 mm in height (representing about 40 mg) was punched out. It was directly placed in a seal that was weighed and immediately sealed. The seal was heated from 25 °C to 95 °C at 5 °C/min, and the onset of gelatinization temperature and enthalpy change were determined as by Mestres, Dorthe, Akissoé, and Houhouigan (2004).

2.4. β-glucan determination

The rest of the quarter sample was freeze dried before β-glucan content was assayed using the mixed linkage β-glucan kit by Megazyme (Ireland). β-glucans were broken down into glucose by the successive action of lichenase and β-glucosidase. The glucose produced was then tested using a glucose oxidase peroxidase reagent.

2.5. Preparation of pounded yam in the laboratory

In the traditional method of preparation, yams are boiled for 15–20 min. From preliminary studies and a kinetic model of cooking yam slices (30 mm in height × 50–100 mm in diameter), it

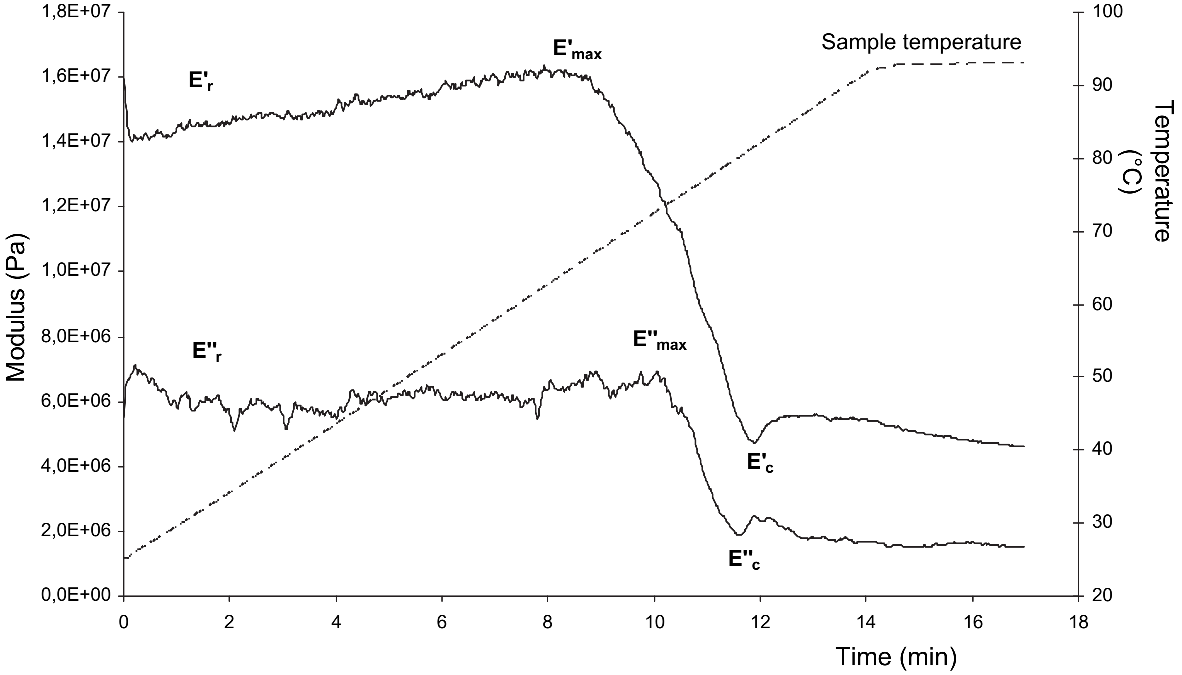

Fig. 1. Typical curves extracted by DMA (from the Kokoro cultivar). E'_r: storage modulus for raw yam pieces (2–4 min running time); E''_r; loss modulus for raw yam pieces (2–4 min running time); E'_c : storage modulus for cooked yam pieces (6–9 min running time); E''_c : Loss modulus for cooked yam pieces (6–9 min running time); E'_{max}: maximum storage modulus for yam pieces (6–9 min running time); E''_{max}: maximum loss modulus for yam pieces (6–9 min running time).

was found that a temperature of around 80 °C is reached at the centre after 10 min in boiling water. Taking this result and the traditional method of preparation into account, the duration of cooking was set at 15 min. Hot boiled yam was then rapidly pounded while hot water was added to adjust the textural quality of the pounded yam to the desirable level. In our laboratory procedure, the dry matter of pounded yam was rapidly determined and adjusted to 25 g/100 g (wb).

The yam tuber was divided into three sections of equal length (head, middle and tail), and each section was cut into slices 30 mm in depth and peeled. One or 2 slices weighing about 200 g were cooked for 15 min in a double volume of boiling water (400 g). The water was drained off and the cooked yam kept hot (a lid was added and the cooking beaker wrapped in a piece of thick material). In the meantime, the dry matter content of cooked yam was determined using an infrared moisture meter (Precisa 310 M, Dietikon, Switzerland) working at 105 °C. About 150 g of boiled yam pieces were first blended for 6 s in a blade blender (Grindomix 200, Retsch, Haan, Germany); then, after adding the amount of hot water (cooking water) required to adjust the dry matter content (25 g/100 g, wb), the sample was blended again for a further 6 s. Four samples of pounded yam (30 g) were weighed in containers that were closed and placed in an oven at a temperature of 50 °C for 30 and 60 min respectively before the firmness and adhesiveness tests were performed. The dry matter content of fresh and pounded yam was also determined using the infrared moisture meter.

2.6. *Tack test*

Dough springiness and stickiness were evaluated through a tack test using a texture analyzer (Model TAXT2, Stable Micro System, UK), equipped with a 5 kg load cell. A Chen–Hoseney stickiness cell was used in combination with a cylindrical Plexiglas probe (diameter 25 mm). The latter was covered with a filter paper using double-sided scotch tape to enhance the adhesiveness between the pounded yam and the surface of the probe.

About 5 g of pounded yam stored at 50 °C was transferred into the Chen–Hoseney stickiness cell that had been previously equilibrated at 40 °C. The dough was extruded through the mesh by rotating the screw. The extruded dough was removed from the surface of the lid using a spatula. Extrusion was repeated to obtain an extrudate 1 mm in height. The cell was placed under the probe which was driven at 0.5 mm/s to compress the sample with a maximum force of 1 N, applied for 0.1 s. The probe was then driven back over a distance of 4 mm at 0.2 mm/s. Four to six measurements were made per dough (after renewing the extrudate each time) within a period of 10 min: the dough temperature was measured at around 40 °C throughout the procedure. Two dough samples were analyzed per section; the mean value for one tuber was thus based on 12–18 measurements.

2.7. *Dough firmness*

The firmness of the pounded yam was measured with a 4301 Instron universal testing machine (Canton, USA) in combination with a 1 kN capacity load cell. A parallelepipedic extrusion cell (25 × 25 mm in width and 100 mm in depth) with an extrusion plate with 2 mm diameter holes was used.

About 33 g of warm (50 °C) pounded yam were placed in the extrusion cell that had previously been equilibrated at 50 °C. The probe (also equilibrated at 50 °C) was then driven downwards at 100 mm/min for a total distance of 95 mm. It first compressed the dough and then extruded it through the mesh. The dough temperature was around 45 °C after extrusion. The mean pressure value measured during the extrusion zone was taken as an indicator of firmness. Two dough samples were analyzed per section: the mean value for one tuber was thus based on six measurements.

2.8. *Swelling power, starch and soluble amylose*

The swelling power, soluble amylose and starch were determined using the method of Brunnschweiler et al. (2006) with slight modifications: 1 g of freshly prepared pounded yam was dispersed (by extrusion through a garlic press) in 30 mL distilled water maintained at 66 °C. The dispersion was prolonged for 20 min with gentle magnetic stirring, followed by centrifugation at 5000 g for 5 min. The swelling power was calculated from fresh and dry sediment weights. Soluble amylose and starch were determined after iodine complexation by measuring the optical density at 545 nm and 620 nm (Nago, Akissoë, Matencio, & Mestres, 1997).

2.9. *Microstructure of raw, boiled and pounded yam*

2.9.1. *Scanning electron microscopy (SEM)*

Fractured raw or cooked yam pieces were observed by scanning electron microscopy (SEM). Cylinders of raw yam (10 mm in diameter, 20 mm in length) were punched out from the yam cross-section. They were then fractured using the 3-point bend test with an Instron universal testing machine. The cooked samples (2 min cooking time in boiling water) were fractured by hand. The fractured sections were cut (10 mm in diameter, 0.5 mm in height) and frozen with liquid nitrogen. The samples were fixed using 6 g/100 g glutaraldehyde (1.8 mL glutaraldehyde, 15 mL 0.2 mol/L cacodylat buffer pH 7.4 in 13.2 mL water). After dehydration in graded ethanol series and dry acetone, critical-point drying samples were fixed

Table 1
Effect of cultivar on raw and pounded yam characteristics.

Yam cultivar	Dry matter of raw tuber (g/100 g, wb)	β-glucan (mg/g; db)	Dry matter of pounded yam (g/100 g, wb)	Extrusion force (N/cm^2)	Maximum force (N)	Area (N s)	Distance (mm)	Soluble starch (g/100 g, db)	Soluble amylose (g/100 g, db)	Swelling power (g/g db)
Anago	40.6 b	0.07 b	26.1	5.1 a[a]	0.26	1.7 a	3.2 a	32.1 abc	10.7 ab	22.2 ab
Florido	24.5 c	0.06 b	23.3	2.8 b	0.24	0.9 bc	1.6 b	35.0 abc	9.6 ab	23.5 a
Gnidou	34.9 c	0.04 b	25.6	4.4 a	0.27	1.1 b	1.7 b	22.3 c	7.1 b	15.6 b
Kokoro	40.8 b	0.10 a	25.6	4.6 a	0.22	1.0 bc	1.9 b	40.8 ab	13.1 a	20.4 ab
Laboco	48.6 a	0.05 b	25.0	2.6 b	0.24	0.6 c	1.1 c	24.8 bc	5.5 b	15.3 b
Morokoro	29.8 d	0.05 b	24.9	2.1 b	0.23	1.0 bc	1.7 b	46.6 a	10.8 ab	24.0 a
Standard error of residual	1.5	0.02	1.2	0.7	0.03	0.2	0.3	6.8	6.9	3.3

Values in same column with different letters are significantly different at 0.05 level.
wb: wet basis; db: dry basis.
Replications: 3 (6–12 determinations).

[a] Mean values extracted at 25 g/100 g dry matter of pounded yam.

Table 2
Effect of tuber section on raw tuber composition and on DMA[a] and DSC parameters.

Tuber section	Dry matter of raw tuber (g/100 g, wb)	β-glucan content (mg/g; db)	E'_r	E''_r	E'_{max}	E''_{max}	E'_c	E''_c	Onset (°C)	Peak (°C)	Enthalpy (J/g, db)
1 (Tail)	31.5 a	0.06	59.0 b	17.9 b	63.7 b	20.7 b	44.4 bc	13.7 b	69.3 c	73.7 c	10.0
2	34.1 b	0.07	51.9 b	16.4 b	54.0 b	20.3 b	40/6 c	15.3 b	69.8 bc	73.9 bc	10.4
3	35.7 bc	0.05	57.0 b	18.3 b	62.0 b	20.6 b	46.2 bc	15.2 b	70.2 b	74.4 bc	10.5
4	37.2 c	0.06	58.9 b	19.0 b	65.8 b	21.8 b	49.6 b	16.2 b	70.4 b	74.7 ab	10.1
5 (Head)	35.6 bc	0.06	75.1 a	25.0 a	82.3 a	28.8 a	61.3 a	21.3 a	71.2 a	75.5 a	9.9
Standard error of residual	1.1	0.01	6.7	2.0	7.3	2.8	5.2	2.3	0.6	0.7	0.6

Values in same column with different letters are significantly different at 0.05 level.
E'_r: storage modulus for raw yam pieces (2–4 min running time).
E''_r: loss modulus for raw yam pieces (2–4 min running time).
E'_c : storage modulus for cooked yam pieces (6–9 min running time).
E''_c : Loss modulus for cooked yam pieces (6–9 min running time).
E'_{max}: maximum storage modulus for yam pieces (6–9 min running time).
E'_{max}: maximum loss modulus for yam pieces (6–9 min running time).
Replications: 4 per section.
[a] Mean values (10^4 Pa) adjusted for 5 mm tickness and 5 mm width.

with Leit-C on aluminium stubs and sputter-coated with platinum before SEM observation (Hitachi S-700, Mito, JP-Tokyo) at 10 kV.

2.9.2. Light microscopy (LM)

Cryosections (10 μm) of pounded yam were prepared, coloured with iodine and observed by light microscopy as described by Brunnschweiler et al. (2006)

2.9.3. Confocal laser scanning microscopy (CLSM)

Raw yam tissue was observed by Confocal Laser Scanning Microscopy using a Leica TCS SP CLSM equipped with an inverted DM RXE fluorescent light optical microscope (Leica Lasertechnik GmbH, DE-Heidelberg) working with Ar/Kr laser. The excitation wavelength was 488 nm, and the emission was recorded between 500 and 580 nm. The yam sections (300 μm thick, 10 mm in *diameter*) were manually cut using microtome blades and immersed in 0.1 mL/100 mL (v/v) acridin orange for 15 min. After rinsing with water, they were mounted on glass slides and observed by CLSM.

2.10. Statistical analysis

Statistical analyses were performed with Statistica 7 (StatSoft, Tulsa, USA) using Anova and general linear model (GLM) procedures, Newman–Keuls mean comparisons, correlation and linear multiple regression models.

3. Results

3.1. Dry matter content of yam products

The dry matter content (DM) of raw yam tuber ranged between 24.5 and 48.6 g/100 g (wet basis). The cultivar Florido had the lowest dry matter content, and Anago had the highest (Table 1). DM content increased significantly from the tail (distal part) to head (proximate) by 4 points (Table 2). Despite the variability observed in raw tubers within and between cultivars, the dry matter of pounded yam was almost constant at around 25 g/100 g (db; Table 1). However, pounded Florido yam exhibited lower DM, due to the very low DM of the raw tuber and despite the fact that no water was added during pounding. Fig. 2 shows the relation between the dry matter content of cooked (DMC) and raw yam (DMR) pieces. The dry matter content of cooked yam decreased only slightly (by 4 g/100 g wb) during cooking, and can be predicted by the value of raw yam (DMC = 0.964 × DMR, with a coefficient of determination of 0.96); so swelling during cooking is actually very limited.

3.2. Pounding behaviour indices

Due to the low values measured for Florido, the effect of the DM of pounded yam was tested. GLM analysis, including DM as co-variable, confirmed the significant effect of DM on firmness; indeed the actual measured value for Florido was underestimated by 0.5 point as compared to the estimated firmness values for 25 g/100 g DM pounded yam for the other cultivars. However, this did not drastically change the classification of the cultivars: Morokoro, Laboco and Florido had low firmness values (Table 1), while the other three cultivars high values.

During the tack test, the maximum adhesive force, the work of adhesion (area under the curve) known as adhesiveness, and the distance of adhesion (distance before adhesive force goes to zero) were measured. The maximum adhesive force was similar in all cultivars (Table 1), but significant differences were observed in adhesiveness and distance of adhesion. Laboco had the lowest values (0.6 N s and 1.1 mm), and Anago the highest (1.7 N s and 3.2 mm).

Soluble starch and amylose ranged between 22.3 and 46.6 g/100 g (db) and between 5.5 and 13.1 g/100 g (db), respectively. Laboco and Gnidou had the lowest values as well as the lowest starch swelling values.

3.3. Thermal (DSC) and mechanical (DMA) properties of yam tuber

Thermal properties (onset, peak, enthalpy change) were significantly affected by the cultivar. Anago and Laboco (*D. rotundata*)

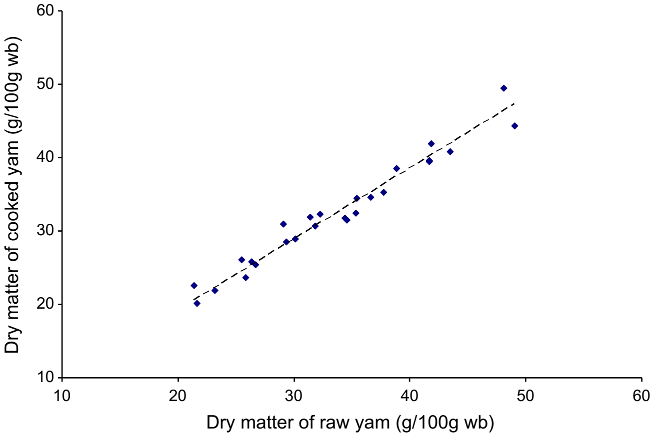

Fig. 2. Relation between dry matter of raw and cooked pieces of yam for pounding.

Table 3
Effect of cultivar on DMA[a] and DSC (gelatinization) parameters.

Yam cultivar	E'_r	E''_r	E'_{max}	E''_{max}	E'_c	E''_c	Onset (°C)	Peak (°C)	Enthalpy (J/g, db)
Anago	87	25	94	28	66	21	68.0 b	72.3 b	10.7 b
Florido	86	24	93	27	62	19	72.2 a	75.7 a	12.8 a
Gnidou	78	24	84	26	57	19	71.5 a	75.6 a	9.4 c
Kokoro	77	26	84	29	67	23	70.4 d	74.9 a	9.0 c
Laboko	86	26	89	28	62	19	66.6 c	71.6 b	9.7 c
Morokoro	85	27	94	30	64	21	71.7 a	75.8 a	9.5 c
Standard error of residual	11	4	12	4	9	3	0.3	0.3	0.2

Values in same column with different letters are significantly different at 0.05 level.
E'_r: storage modulus for raw yam pieces (2–4 min running time).
E''_r: loss modulus for raw yam pieces (2–4 min running time).
E'_c: storage modulus for cooked yam pieces (6–9 min running time).
E''_c: Loss modulus for cooked yam pieces (6–9 min running time).
E'_{max}: maximum storage modulus for yam pieces (6–9 min running time).
E''_{max}: maximum loss modulus for yam pieces (6–9 min running time).
Replications: 2 (20 determinations per tuber).
[a] Mean values (10^4 Pa) adjusted for 5 mm thickness and 5 mm width.

showed the lowest onset and peak temperatures (Table 3), whereas Florido (*D. alata*) had the highest enthalpy change (12.8 J/g db). In addition, cutting the tuber into sections significantly affected the gelatinization temperature (Table 2): onset and peak temperatures increased by 1.8 °C from tail to head.

Fig. 1 shows the typical curves recorded during a DMA run. Storage modulus (E' referred to as elasticity) and loss modulus (E'', viscosity) first increased slightly and reached maximum values by 60–70 °C, then dropped to a minimum value near 80 °C (Fig. 1) and finally increased at the end of the run. Six parameters were taken from this curve to describe the mechanical behaviour of yam during cooking. E'_r and E''_r were the modulus of raw (uncooked) pieces of yam; they were calculated as the mean values between one and 2 min, i.e. when the yam pieces were at a temperature of between 30 and 35 °C. E'_c and E''_c, the modulus of cooked pieces of yam, were the minimum values determined between 10 and 13 min (i.e. between 75 and 90 °C). In addition, E'_{max} and E''_{max} measured between 7 and 9 min (60–70 °C) were also calculated. Tanδ (not shown) did not evidence any clear transition; indeed storage and loss modulus varied in parallel throughout the run.

Sample width and height (co-variables) significantly and negatively affected elastic and loss modulus, which were consequently adjusted for parallelepipeds 5 mm in width and height. Major variations were observed between replications using the same tuber section, but the high number of replications (4 per section and 20 per tuber) provided evidence of a significant effect of tuber section (Table 2): the head of the tuber showed higher values for storage and loss modulus throughout the DMA run. However, significant differences between cultivars were rarer (Table 3); Gnidou displayed lower elastic modulus in both the raw and cooked state, E'_r and E'_c respectively, whereas Laboco and Florido displayed similar behaviour for E' and E'' at any given time.

3.4. β-glucan content

β-glucan content was determined on 5 sections for each cultivar. It was very low, ranging between 0.04 and 0.10 g/100 g (db). A significant cultivar effect was evidenced: Kokoro had the highest value, with no section effect (Tables 1 and 2).

3.5. Microstructures during the pounding process

Microstructures (cell walls and starch granule, fracture plane) were observed on raw, boiled and pounded Laboco, Gnidou and Florido cvs, which exhibited the most varied sensorial attributes. Akissoe et al. (2008) showed that Laboco ranked highest for elasticity and smoothness (around 13–14 for both attributes, for a maximum value of 17.5) whereas Florido ranked lowest (with less than 3 for both attributes). Observed by CLSM, cut sections of raw yam showed 100–200 μm cells (irrespective of the cultivar) almost completely filled with densely packed starch granules (Fig. 4). In Florido, the cell walls of two adjacent cells were clearly separated, whereas in Laboco they appeared to be merged. The thickness of double cell walls was 7 μm in Florido, whereas that of merged adjacent cell walls was by 5 μm in Laboco. The rupture surface of raw and cooked yam was observed by SEM (Figs. 5 and 6). In raw tubers, fracturing occurred through cell walls, revealing opened cells, whatever the cultivar. In contrast, in cooked yam, rupturing revealed the surface of the cell walls, with in addition some fractured cells in Florido (Fig. 6). The cell surface appeared rough, particularly in Laboco.

Iodine stained cryosections of pounded yam were observed by light microscopy (Fig. 7). The cell structure almost completely disappeared. A heterogeneous blue gel made of extra-cellular dispersed starch was observed, with some residual cell walls (cw) and minor intact cells (ic). No clear difference was observed in the microstructure of pounded Florido, Laboco or Gnidou yams (data not shown).

4. Discussion

4.1. Pounding behaviour

Several surveys provided evidence that Laboco is the preferred cultivar for pounding, unlike Florido (Dansi, 2001; Hounhouigan et al., 2003). Sensorial analysis confirmed that pounded yam prepared with Florido had very weak elasticity and smoothness in contrast to pounded yam prepared from other cultivars and particularly from Laboco (Akissoe et al., 2008). However, the instrumental measurements performed in this study failed to provide clear

Table 4
Correlations between the textural quality of pounded yam and the physico-chemical parameters of raw and pounded yam.

	Raw yam characteristics[a]				Pounded yam characteristics[b]			
	Gelatinization onset (°C)	Gelatinization peak (°C)	Gelatinization enthalpy (J/g, db)	β-glucan (mg/g; db)	DM of pounded yam (g/100 g, wb)	Soluble starch (g/100 g, db)	Soluble amylose (g/100 g, db)	Swelling power (g/g, wb)
Peak force (N/cm^2)	−0.23	−0.24	−0.21	0.47	0.61 **	−0.36	0.03	−0.30
Adhesive force (N)	0.15	0.10	0.07	−0.63	−0.16	−0.46*	−0.34	0.33
Area under curves (N sN.s)	0.03	−0.06	0.24	−0.12	0.39	0.02	0.30	0.03
Distance (mm)	−0.03	−0.12	0.30	0.30	0.34	0.11	0.36	−0.02

*Significant at 0.05 level.
**Significant at 0.01 level.
[a] Degree of freedom (df) = 4.
[b] df = 23.

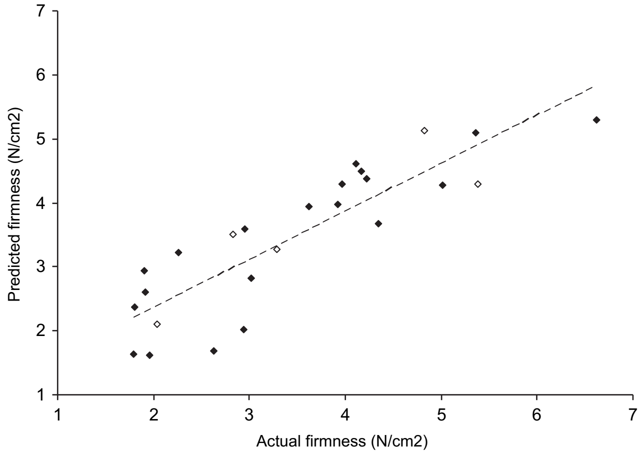

Fig. 3. Relationship between actual (measured) and predicted (from the model) firmness of pounded yam (■ model samples; □ validation samples).

evidence in support of this classification of the cultivars; Laboco and Florido did not display opposite values during the extrusion and the tack tests. However, pounded yam prepared from Laboco had slightly lower values of adhesiveness, distance of adhesion and amylose solubility. This difficulty in assessing texture by instrumental methods is not new, and previous studies on pounded yam (Akissoe et al., 2008) or amala (Akissoe, Hounhouigan, Mestres, & Nago, 2006), which is a thick paste made from yam flour, also failed to evidence clear relationships between sensorial and instrumental texture.

4.2. *Thermo-mechanical behaviour*

One of the objectives of this work was to evaluate the relationships between the mechanical properties of the tubers during cooking (monitored using DMA) and that of pounded yam. A slight increase in E′ and E″ was observed with a maximum around 60–70 °C, which could be partially related to the initial but reversible swelling of starch granules. The shift of water from cell cytoplasm or cell wall to starch increased the hardness of these structures. After this period, the subsequent softening of yam pieces with minimum storage and loss modulus values near 80 °C clearly coincided with the starch gelatinization that occurred at the same temperature, as evidenced by DSC. This phenomenon indeed increased starch polymer mobility and reduced E′ and E″ values.

Marked variations were observed between replications for storage and loss modulus, which can be attributed to the high heterogeneity in the material as already pointed out by Böhler, Escher, & Solms (1987). Böhler et al. (1987) reported major variations among potato tubers of the same cultivar and within individual tubers. Yam tuber parenchyma presents randomly distributed vascular bundles and radial adjacent structures with a diameter of 1–5 mm (Brunnschweiler, 2004). In the present study, relatively large samples (section 5–6 × 5–6 mm) were consequently chosen for the bending test to try and reduce the

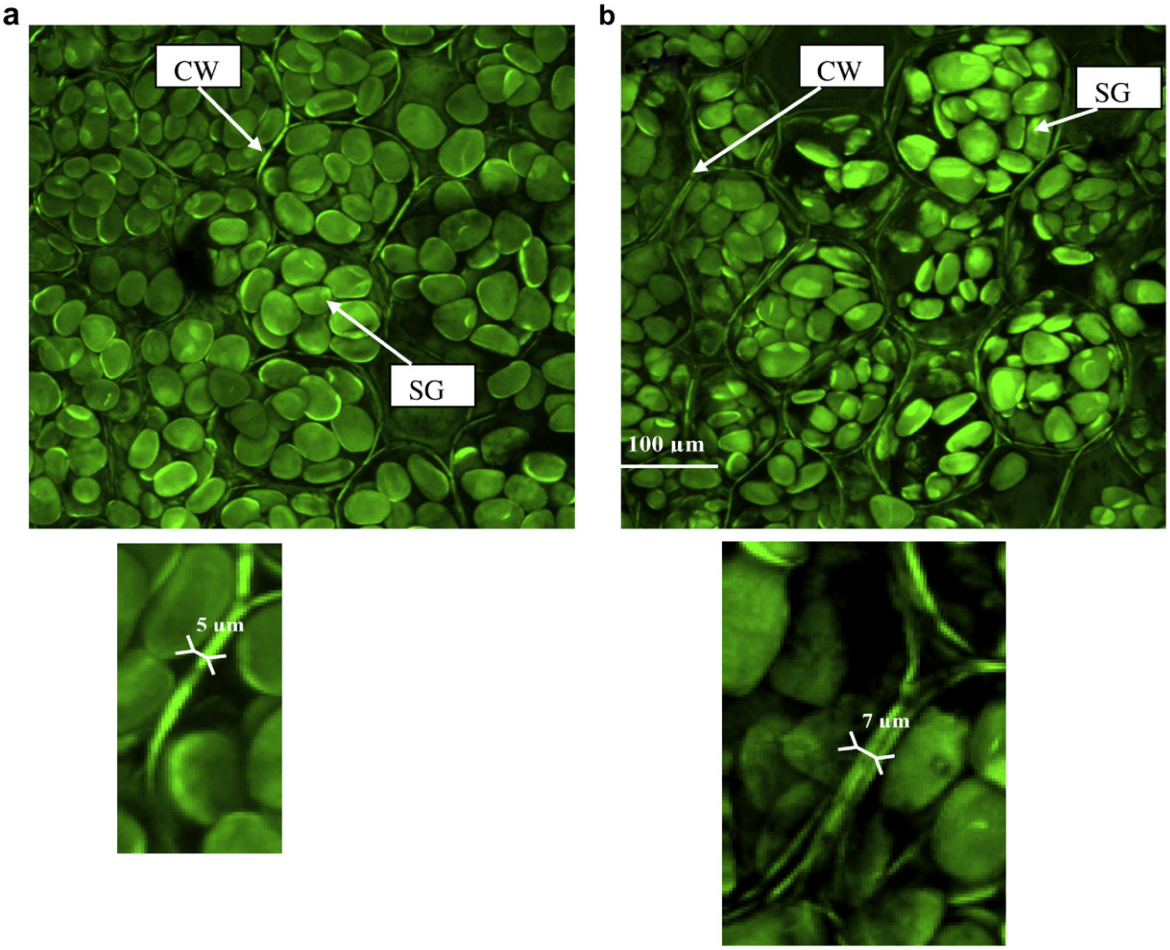

Fig. 4. Fracture of raw yam tubers of Laboco (a) and Florido (b) cultivars observed by Confocal Laser Scanning Microscopy; cell walls (CW) and starch grains (SG).

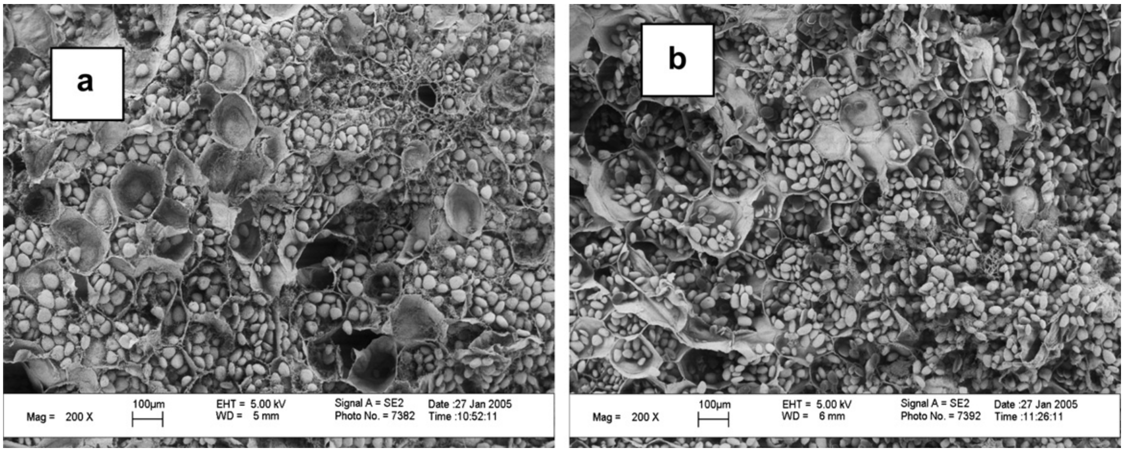

Fig. 5. Fracture of raw yam tubers of Laboco (a) and Florido (b) cultivars observed by Scanning Electron Microscopy.

variation. This came at the expense of the correlation of modulus with sample depth and width that indicated that the test was not a real bending test but rather a compression test. In addition, deformation was very low (about 1 mm) and perhaps insufficient to evidence differences in bending behaviour.

Processors generally say that yam suitable for pounding exhibits high mealiness, or friability. It was therefore hypothesized that the textural properties of yam pieces could be evaluated using DMA, and that Laboco and Florido should exhibit clear differences in some measured moduli. We were however unable to show any significant differences between Laboco and Florido using DMA. More generally, no significant correlation was found between DMA and the measured textural parameters of pounded yam. Florido exhibited the highest onset of gelatinization temperature (72.2 °C) and Laboco the lowest (66.6 °C). The experimental conditions used for the DMA test may partly explain the lack of discrimination between cultivars. In addition, the effect of water content may also have masked a difference; the modulus significantly increased from tail to head of the tuber in parallel with dry matter content. The moduli of Florido samples, which have lower DM, were therefore underestimated. Brunnschweiler et al. (2006) recently claimed that pounded yam properties are linked to cell disintegratability, i.e. friability, but no clear relationship between these two attributes was evidenced in a collection of *D. alata* (Egesi et al., 2003). This relationship therefore needs further study.

4.3. Dry matter and starch solubility determine pounded yam texture

The invariability of pounded yam DM has recently been reported (Akissoe et al., 2008) Indeed, well-informed processors have the empirical ability to identify and adjust the DM content of pounded yam, irrespective of the DM of the original tuber. It was therefore necessary to adjust the dry matter content during pounding in our laboratory test. It has been shown that yam pieces do not swell a lot during cooking, and that cooked yam DM can be predicted from raw tuber DM. The quantity of water required to adjust pounded yam DM content can therefore be easily calculated. The raw tuber DM varied enormously (24.5–48.6 g/100 g wb), but the DM of pounded yam varied only slightly (23.3–26.1 g/100 g wb).

Nevertheless, the DM of pounded yam DM remained the most significant variable correlated with the textural attributes of pounded yam (Table 4). It was highly correlated with firmness as measured by extrusion. Multiple regressions showed that in addition to DM, soluble starch (St) and amylose (Amy) concentrations can be used to predict the firmness with a high determination coefficient (0.75):

$$\text{Firmness}\left(\text{N/cm}^2\right) = -6.18 + 0.41 \times \text{DM} - 0.14 \times \text{St} + 0.45 \times \text{Amy}$$

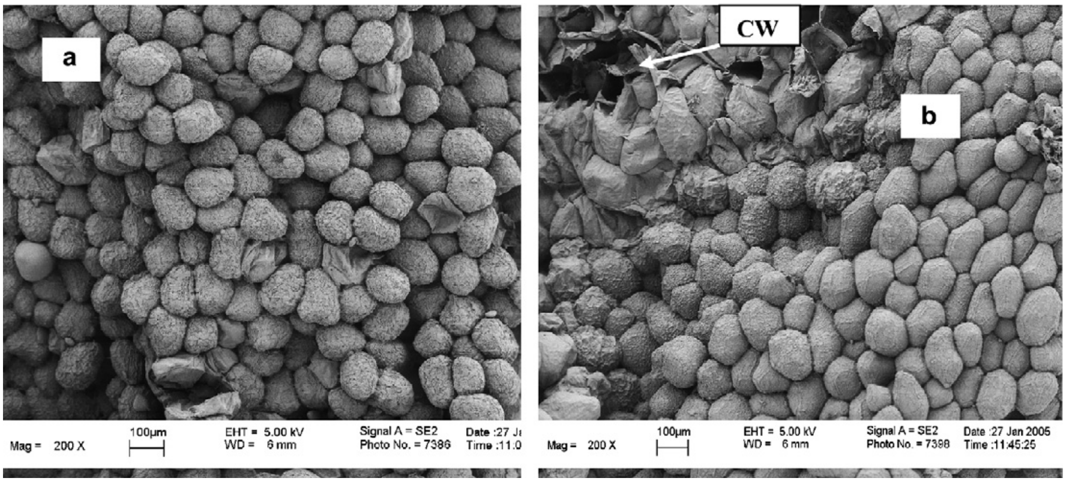

Fig. 6. Fracture of pieces of yam observed by Scanning Electron Microscopy after boiling for 2 min: Laboco (a) and Florido (b) cultivars.

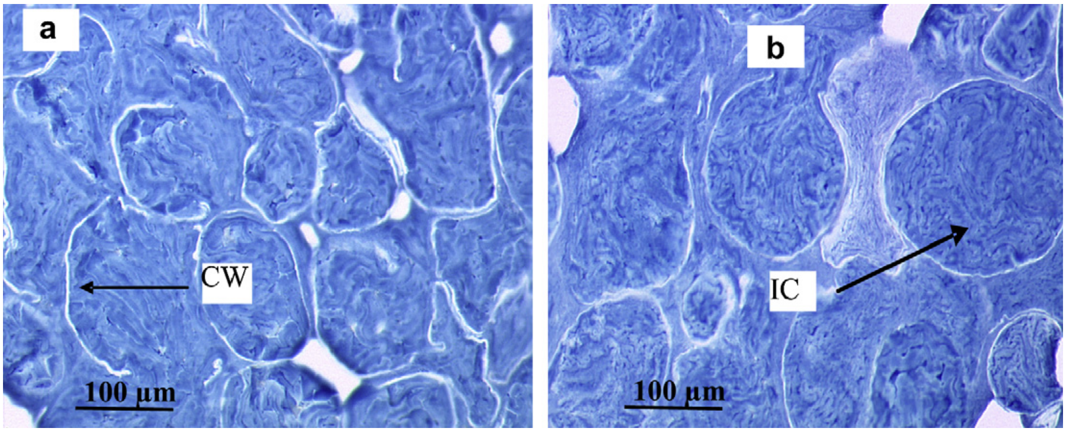

Fig. 7. Cryosections of pounded yam stained with Lugol (a, Laboco cultivar; b, Florido cultivar); magnitude of 100; CW, cell wall; IC, intact cell.

The plot of the actual versus predicted values shows the precision of the regression (Fig. 3), which was also able to predict five validation samples that were not used in the model. Firmness increased with the solubilisation of amylose, a macromolecule that rapidly forms a gel (Miles, Morris, Orford, & Ring, 1985), but decreased with overall soluble starch. The latter relationship may be an indicator of the level of disintegration of the cells and starch. Pounded yam is indeed a composite material composed of a continuous starch phase with dispersed cells (Brunnschweiler et al., 2006). Intact cells and starch may thus reinforce pounded yam, increasing its firmness, as is the case for starch gels (Mestres, Nago, Akissoë, & Matencio, 1997; Ring & Stainsby, 1982). Previously, Gnidou was shown to have the highest amylose content: 26.6%, db versus about 21% for other cultivars, particularly Laboco and Florido (Akissoe et al., 2008), but in this study Gnidou had one of the lowest soluble amylose concentrations in pounded yam (7.1 g/100 g, db; Table 1). Indeed, there did not appear to be direct relationship between the amylose content of raw tuber and soluble amylose concentration in pounded yam.

4.4. *Impact of microstructures on yam products during pounding*

As previously observed in yam (Brunnschweiler, 2004) and potato (van Marle et al., 1992), the fracture of raw yam tubers occurred across the cells, revealing their contents (starch granules). This indicates that cell-to-cell adhesion is higher than cell wall strength in raw tubers (Brunnschweiler, 2004). On the other hand, in cooked yam the fracture almost only occurred between adjacent cells. This may be related to the solubilisation and/or degradation of pectin which is involved in the adhesion of cell lamella (Bourton, 1989; Stolle-Smits, Donkers, van Dijk, & Sassen, 1998).

In Florido, fractures passed also through some cells, which can be interpreted as being due to higher inter-cellular adhesion. Mealiness of roots and tubers is generally connected to separation of intact cells rather than rupture (Onayemi, Babalola, & Badanga, 1987), due to disintegration of middle lamellae (Favaro, Beleia, da Silva Fonseca Junior & Waldron, 2008); cells “round off” during cooking and become easily separable. Conversely, lack of mealiness appears to be connected to thicker cell walls (Otegbayo et al., 2005) and resistant middle lamellae (Favaro et al., 2008). Accordingly, CLSM revealed a *larger* cell wall for Florido with distinct double cell walls for adjacent cells. Florido should therefore exhibit lower friability, as generally observed in *D. alata* cultivars (Otegbayo et al., 2005).

The ratio of intact cells (e) to extra-cellular starch in pounded yam micrographs probably explains the difference in rheological behaviour and texture of different pounded yams, as already pointed out (Brunnschweiler et al., 2006). However, it is difficult to assess these structures, in particular due to the heterogeneity of the product, although starch solubility may be an indirect measurement of cell and starch destructuration, as shown by the firmness model. This result could probably be improved by determining pectin content, the component of middle lamellae involved in cell–cell adhesion, and its structure. This would provide the information required for understanding and assessing yam mealiness and pounding behaviour. Pectic components and their interaction with divalent cations definitely contribute to ease of cooking and tissue softening during the cooking of cassava (Favaro et al., 2008). On the other hand, β-glucan does not appear to play a direct role in the texture of pounded yam, as we found no significant correlation between β-glucan content and the texture of pounded yam (Table 4).

5. Conclusion

Instrumental measurements of the texture of pounded yam failed to discriminate yam tubers suitable for pounded yam that were in agreement with the results of previous sensorial analyses (Akissoe et al., 2008). In addition, none of the thermo-mechanical parameters measured during the cooking of tubers was able to describe the quality of pounded yam. However, Florido, known for its inferior textural quality in the form of pounded yam, displayed thicker and well-defined double cell walls and middle lamella. Further studies will thus focus on pectin, one of the major constituents of middle lamella that is also responsible for cell–cell adhesion.

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