Rheological and textural studies of arrowroot (*Maranta arundinacea*) starch–sucrose–whey protein concentrate gels

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Abstract The aim of this work was to study the effect of adding whey protein concentrate and sucrose on the rheological and textural properties of the gels obtained from arrowroot (*Maranta arundinacea*) starches. It was found that the starches evaluated presented low levels of protein, ash, lipids and acidity. Arrowroot starch of the common and round root varieties presented 17.80 and 35.96% of amylose content, respectively. The swelling power of the starch from common variety was higher than that of the round root but the solubility index was lower. Dynamic rheological measurement showed strong gel behavior and formulated gels with 4% sucrose and 1% protein were more elastic than the other formulations. Gels formulated with starch of the round root presented a higher gelatinization temperature than gels formulated with the common. The firmness of gels was directly proportional to the sucrose level, while the increase in the protein content led to reduction in the same.

Keywords *Maranta arundinacea* · Texture · Rheology · Round root · Common

Introduction

In agro-food industries starches and derivatives are used as ingredients, basic components or additives added in small amounts to perform various functions, such as thickeners, binders, disintegrants, stabilizers, texture modifiers, gelling and bulking agents. They therefore perform an important role in controlling the characteristics of a great number of processed foods (Otegbayo 2014). The most common sources of starch are corn, wheat, cassava and potato. However, in recent years unconventional starches (starches from raw materials that are not commercially used for extraction) are increasingly gaining importance due to their potential application in the development of new products and/or improve traditional uses (Torruco-Uco and Betancur-Ancona 2007; Sweedman et al. 2013; Albano et al. 2014; Charles et al. 2016). Among these sources considered unconventional are the arrowroot, Peruvian carrot, taro and sago. These tubers and roots have carbohydrate content and nutritional value very similar to corn and rice (Aprianita et al. 2014).

According to Charles et al. (2016), the term arrowroot refers to any plant of the genus *Marantha*, but the term is most commonly used to describe the easily digested starch from rhizomes of *Maranta arundinacea*. The Brazilian arrowroot (*Euphorbiaceus* family) is a perennial herbaceous, rhizomatous plant, which features a bright and scaly bark. The rhizomes are fusiform and very fibrous, forming the reserves for development of a new plant (Leonel et al. 2002). These traditional starchy plants may be important in the human diet to reduce the risks of obesity, cardiovascular diseases and diabetes. Furthermore, these tubers and roots are free of gluten and therefore may also replace wheat in certain food applications to reduce the incidence

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of celiac disease (CD) or other allergic reactions to gluten (Van Hung and Morita 2005).

Arrowroot starch presents a binding temperature above 70 °C and its amylose content may vary from 16 to 27% (Moorthy 2002). This content varies with botanical sources, plant maturation levels and even within cultivars of the same species. The potential of arrowroot has not been fully utilized, mainly due to lack of general knowledge on technological and functional properties of the material. Thus, there is a need for further studies to introduce arrowroot starch into the human diet, since it presents characteristics such as easy gelation capacity, absence of gluten, high digestibility and medicinal properties (Jyothi et al. 2010; Kumalasari et al. 2012). Arrowroot starch may also be used in various bakery products, gels and special binders, ice cream stabilizers and others, in substitution for other types containing gluten (Jyothi et al. 2010).

Considering that starch is not encountered alone in food products, it is important to study its interaction with components such as protein and sucrose, since products such as breads, pastas, soups, sauces, breakfast cereals and other processed foods have characteristic texture and sensory attributes related to the presence of different proportions of such components in their formulations. For example, the starch gelatinization process is influenced by the presence of other compounds like sucrose and protein, which directly or indirectly affect the water activity and the microstructure of the starch (Sumnu et al. 1999). According Spies and Hoseney (1982) sucrose, delays gelatinization through a combination of two independent mechanisms: (1) lowering water activity (A_w) of solution and (2) interacting with starch chains to stabilize the amorphous regions of the granule. Since the rheological and textural properties are affected during the gelatinization process, their evaluation is important.

Based on the above considerations, the aim of this work was to study the effect of adding whey protein concentrate and sucrose on the rheological and textural properties of the gels obtained from starch of the common arrowroot and round root varieties. A second objective was to determine the physicochemical characteristics of the starches, because these properties directly affect the starch gelatinization process.

Materials and methods

Materials

Producers of Conceição do Almeida—BA, Brazil, kindly supplied starches from arrowroot (*Maranta arundacea*) of common and round root varieties. Whey protein concentrate (100% pure Whey Protein) were purchased from Max

Nutry and commercial sucrose from local supermarket. All others chemicals used were of Analar grade.

Chemical characterization

The concentrations of moisture, ash, protein and pH were determined by the methodology suggested by the Association of Official Analytical Chemists (1997). The total lipid content was determined by the method of Bligh and Dyer (1959). In the quantification of the apparent amylose was used the colorimetric method, based on light transmission through a colored complex that amylose forms when reacting with iodine, according to the methodology of Martínez (1989). All analyses were performed in triplicate.

Scanning electron microscopy (SEM)

Visualization of starch granules morphology was performed by using a scanning electron microscope (LEO 1430 VP, Model VP, UK). The powder samples were placed on double face carbon tape attached to a metal disc, submitted to application of a layer of gold for 2 min and observed in a scanning electron microscope operated at 20 kV.

Swelling power and solubility index

The swelling power and solubility index as a function of temperature were determined according to the methodology proposed by Torre-Gutiérrez et al. (2008) with slight modifications. Starch samples (0.2 g db) were taken in pre-weighed centrifuge tubes and heated with water (20 mL) at 30, 40, 50, 60, 70, 80 and 90 °C for 30 min with continuous stirring to prevent lump formation. After cooling, the dispersion was centrifuged at 2020×g for 15 min. Then supernatant was carefully placed in pre-weighed petri-dishes and dried for 3 h at 105 °C and weighed. The residue obtained after drying of supernatant represented the amount of starch solubilized in water. The swelling power and solubility were determined by Eqs. (1) and (2), respectability.

$$\text{Solubility (\%)} = \frac{\text{Weight of soluble starch}}{\text{Weight of sample}} \times 100. \quad (1)$$

$$\text{Swelling power (\%)} = \frac{\text{Weight of sediment paste}}{\text{Weight of sample} \times (100 - \text{solubility})} \times 100. \quad (2)$$

Samples preparation

For gels preparation, suspensions of starch, water, sucrose and whey protein were obtained by the w/w ratio with a total of 100 g. In samples formulations were used two arrowroot starch concentrations of each variety (10 and 12%), four sucrose concentrations (1, 2, 3 and 4%) and four whey protein concentrations (1, 2, 3 and 4%), in order to evaluate interaction effect between different starch percentages with whey protein, starch with sucrose, the three components together and pure starch. The suspensions were gelatinized at 80 °C in a thermostatic bath for 5 min with gentle shaking by hand to prevent lump formation. These gelatinization conditions were chosen based on preliminary tests.

Gels Texture

The already gelled samples were transferred to 50 mL glass recipients, adjusting the height of the gel to about 70% of the total volume; they were then cooled for 1 h at room temperature and stored in a BOD at 4 °C for 24 h. After the storage period the samples were removed from the BOD and submitted to the texture profile analysis. Three runs were performed in order to evaluate the influence of concentration of solutes (starch, sucrose and whey protein) separately and their interaction on the textural properties of the gels.

TPA (texture profile analysis) of the gels was performed using a Stable Micro Systems Texturometer, UK (TA—HD Plus), equipped with a 50 kg load cell and a probe of 12.7 mm diameter (Delrin P/0,5R). The experimental conditions used were pre-test speed 2.0 mm/s; test speed 2.0 mm/s and post-test speed 2.0 mm/s; 50% compression and a 5 s rest period between the two cycles; trigger force of 4.793 g and a data acquisition rate of 100 points per second. These runs conditions were determined via preliminary tests. To obtain a texture estimate of starch gels, measurements were performed in triplicate for each of the three replications. Programming of the experiment and data collection were performed using the Texture Expert program for Windows 1.20 (Stable Micro Systems, UK).

Rheological characterization

The rheological deformation measures of arrowroot starch gels were performed by dynamic testing in a controlled stress rheometer (Termo Scientific Haake Mars III), with the geometry of parallel flat plates. For each assay 50 g of sample were prepared, which homogenization in an ultra-thermostatic bath microprocessor with circulation at 80 °C for 5 min. In these assays, the voltage, frequency and time sweeps were carried out at constant temperature (30 °C),

where temperature was controlled using a thermostatic bath.

The previously gelatinized samples were characterized based on measurement of mechanical spectra in a Termo Scientific Haake Mars III rheometer, with parallel plate geometry. A smooth stainless steel plate measuring 40 mm in diameter was used. The gap between the plates was 0.1 mm. The sample volume used was 0.5 mL. Before starting the analysis the system was left for 4 min until the entire system entered thermal equilibrium.

Prior to analysis of the mechanical spectra (moduli G' and G'' in function of frequency) a strain sweep was performed in the range of 0.01 to 10 Pa at constant frequency of 1 Hz and temperature of 30 °C in order to determine the viscoelastic region of the starch suspensions. The viscoelastic region is the region where the structure of the gel is preserved, i.e., the storage or elastic modulus (G') and loss or viscous modulus (G'') are independent of frequency. In this study the viscoelastic region was obtained under the tension of 0.05 Pa for all samples. Next, low amplitude oscillatory frequency sweep assays were performed in the range of 0.01–10 Hz at 30 °C at 0.05 Pa.

The stability of the gels was evaluated in function of temperature and time. The time sweep was performed for 15 min at a temperature of 30 °C, 0.05 Pa and 1 Hz and the temperature sweep of the starch solution supplemented with the solute was carried out between 30 and 90 °C at a heating rate 1.2 °C min⁻¹ and 1 Hz. All runs were performed in triplicate. To prevent drying of the starch slurry during the analysis silicone oil was applied to the surface of the sample that was exposed to the external medium.

Statistical analysis

The results obtained in the texture analysis were submitted to analysis of variance (ANOVA) and the effect of interaction between the different percentages of starch with the whey protein, starch with sucrose, and three components together and pure starch was tested. The means of the qualitative data (effect of the starch %) were compared by the *F*-test and the quantitative data (effect of the whey protein % and sucrose %) by regression analysis, at 5% probability. To perform the statistical analyses the system for statistical analyses (SAEG) was utilized. In the present study all analyses were performed in triplicate and with repetition.

Results and discussion

Chemical composition and amylose content

The results obtained from chemical characterization of starch from two arrowroot varieties are shown in Table 1.

The moisture content, in both varieties, is within the safe limit for storage without deterioration of its quality (Mweta et al. 2010). The samples presented ash contents within the ranges reported for tuber starches in literature (Ferrari et al. 2005; Rocha et al. 2008). Both starch had lipid contents < 0.1%, which is a desirable characteristic for starch since a high concentration of lipids can complex with amylose to form a rigid structure which restricts the expansion of starch granules during the cooking process (Hasjim et al. 2010). As expected for starch from roots and tubers, arrowroot starch presented relatively low protein levels. According to Hoover (2001) and Peroni et al. (2006), proteins in starch from tubers are found in small quantities and do not change their functional properties, such as gelation. When the sum of lipids, ash and protein contents is less than 1% of the total the starch is considered to be of high purity, and that the extraction process was efficient (Rocha et al. 2008).

It was observed that the pH was close to 7.0 for the two starch varieties, which is common for native starches, those which have not undergone any fermentation or modification processes, and most of these present pH close to neutral. The apparent starch content for the two varieties were greater than 88%.

Amylose is one of the components responsible for structure of the starch granule and its quantification is of great importance for understanding the behavior of starch binders and gels. The apparent amylose content present in starch of the common arrowroot variety was approximately 50% lower than that of starch from the round root variety, however it was within the limits reported in literature for

this starch (Ferrari et al. 2005; Hernández-Medina et al. 2008). The amylose content has a direct influence on the functional properties of starch. In starches with high amylose content, the molecular mobility is small, requiring higher temperatures in the gelatinization process (Parker and Ring 2001). However, they present better characteristics for use in films, because their structures have higher capacity for reorganization in the drying period. Generally, starches with high amylose contents need to be modified to improve their properties such as texture, retrogradation, and consequently syneresis, where such modifications may be chemical or by addition of other components (BeMiller 2011).

Granules Morphology

The dimensions of the granules are in the range of 10–29 μm in width for granules of the common variety and 7.5–30 μm in width for granules of the round root variety. Most starch granules from both varieties show a wide size distribution, which includes a mixture of large (elliptical to oval), intermediate (oval) and small granules (oval to elliptical) (Fig. 1). The surfaces of all the granules appear smooth and without fissures, indicating that the granules are intact and undamaged. The size and shape of the granules varies with the species, while size distribution varies with the plant developmental stage and form of tuberization (Gunaratne and Hoover 2002). Grain size affects the starch composition, binding and gelling properties, baking characteristics, crystallinity and swelling power (Hitomi et al. 2002).

Swelling power and solubility index

The swelling power for both starch varieties studied does not show great variation at temperatures below 60 °C, because such temperatures are not sufficient to break the hydrogen bonds between polymer chains responsible for the crystalline structure of the granules. Between temperatures of 60 and 70 °C there was a strong increase in the swelling power for both varieties. For temperatures greater than 70 °C this increase was more subtle in both varieties. This behavior is due to the overcoming of the temperature necessary for the beginning of the gelatinization of the starch, which occurs due to the thermodynamic activation of the starch molecules, increasing the granular mobility and consequently the water penetration, facilitating the swelling capacity of the granules. Therefore, the hydrogen bonds of the starch molecules are broken and the water molecules bind to the original. The swelling power of common variety (between 2.06 and 32.92 g g^{-1}) was higher than that of round root variety (between 1.74 and 15.02 g g^{-1}). This difference is due to the amylose content,

Table 1 Chemical characterization of arrowroot starch of the common and round root varieties

Analyses	Varieties	
	Common	Round root
Moisture ^a (%)	10.9 ± 0.07	10.2 ± 0.06
Ashes ^a (%)	0.22 ± 0.00	0.14 ± 0.01
Protein ^a (%)	0.41 ± 0.00	0.27 ± 0.00
Lipids (%)	< 0.1	< 0.1
pH	7.3 ± 0.07	6.8 ± 0.12
Starch (%)	88.46 ± 0.08	89.38 ± 0.02
Amylose (%)	17.8 ± 1.65	35.96 ± 0.73

^aResults expressed on a wet basis

Fig. 1 Electron microscopy images of arrowroot starch granules of the common (a) and round root varieties (b)

which limits swelling of the granule, increasing its resistance through stronger associative forces which maintain the structure of the granules (Peroni et al. 2006).

The solubility index of arrowroot starch suspensions increased for temperatures greater than 50 °C and remained practically constant at temperatures above 70 °C. The arrowroot starch suspensions from the round root heated from 60 to 80 °C showed a higher solubility (between 2.41 and 28.06%) in relation to starch of the common (between 0.15 and 22.11%). This is because solubility is a result of amylose leaching, i.e., the higher the amylose content in starch the greater is its leaching.

Increase of the swelling power and the solubility index with temperature is a function of overcoming the temperature required for the onset of starch gelatinization, which occurs due to thermodynamic activation of starch molecules, increasing the granular mobility and consequently water penetration to increase the swelling capacity of the granules. Thus, the hydrogen bonds of the starch molecules are broken and the water molecules bind to the released hydroxyl groups, promoting irreversible bead swelling to a size many times larger than the original (Hoover 2001).

Gels texture

By statistical analysis it was found that for the starch/sucrose/protein concentrate formulations there was a quadratic effect ($P < 0.01$) for firmness of the gels as a function of increased sucrose concentration and reduced protein concentrate concentration. The minimum point estimated by the regression equation for starch of the common variety occurred at the level of 0.54% sucrose with 0.756 N firmness for gels with 10% starch and 1.1% sucrose with 0.36 N firmness for gels with 12% starch. For the *round root* variety, the minimum point estimated by the regression equation was

1.44% sucrose with 0.286 N firmness for gels with 10% starch and 2.49% sucrose with 0.020 N firmness for gels with 12% starch. The same effect was observed for the starch/sucrose formulation with increasing sucrose concentration. The maximum point estimated by the regression equation for the common variety occurred at the level of 3.22% sucrose with 1.92 N firmness for gels with 10% starch and 3.93% with 2.39 N firmness for gels with 12% starch. For the *round root* the maximum point estimated by the regression equation was 3.26% sucrose with 1.258 N firmness for the gel with 10% starch and 2.40% with 0.707 N firmness for the gel with 12% starch. When analyzing the isolated effect of adding protein concentrate a quadratic effect was observed on firmness of gels from the common variety, due to the increase in protein concentrate levels, while in the formulations with for the *round root* there was a decreasing linear effect on the firmness of gels due to the increase in protein concentrate levels.

For the formulations with 10% starch (Fig. 2), it can be observed that in starch/sucrose formulations with increased sucrose content there was increased firmness of the gels formulated with starch from the common variety up to 2%, and remained unchanged to 3% with a gentle decrease for 4% sucrose. This decrease can be attributed to the lower availability of water that reduces swelling of the starch granules; and therefore there was less release of amylose to the medium and consequently reduced amylose-sucrose interaction, leading to reduced firmness. The round root variety showed increased firmness for all sucrose concentrations studied. Addition of sucrose led to an increase in firmness of gels from the two varieties in relation to the control and decrease in the negative effect of whey protein.

Gels formulated with starch and whey protein were opaque. Gels formulated with proteins are often weak and susceptible to syneresis (Damodaran et al. 2007). This

Fig. 2 Firmness of gels formulated with 10% (**a, b**) and 12% (**c, d**) arrowroot starch of common (**a, b**) and round root (**b, d**) varieties supplemented with sucrose and whey protein concentrate; filled

square: starch/sucrose; filled triangle: starch/protein concentrate; filled circle: starch/sucrose/protein concentrate

explains the fact that with the increase in whey protein there is a loss in firmness of the gels. This behavior can be attributed to the interaction between starch and proteins, where thermodynamically different polymers can cause phase separation with significant consequences in texture (Morris 1990). In this case, phase separation may be segregative, i.e., a given polymer is more concentrated in each formed phase, presenting repulsion among them (thermodynamic incompatibility).

In formulations with starch, sucrose and whey protein it was verified that for the common variety there was a decrease in firmness for the formulation with 2% sucrose which was favored by the higher whey protein levels, and for the other concentrations there was an increase in the firmness of gels. In formulations with the round root variety there was a reduction in firmness from 0 to 1%, while there was an increase in firmness for the other formulations, reaching a level slightly higher for the gel with the same levels of sucrose and whey protein with 10% starch from the common variety.

For formulations with 12% starch and sucrose, gels formulated with the common variety (Fig. 2c) presented an

increase in firmness with sucrose concentration, where these values are slightly higher than those of the formulation with 10% starch (Fig. 2a). In formulations with starch from the round root variety there was a decrease in firmness up to concentration of 2% sucrose and an increase for the other formulations, always lower than the value of the control gel and the formulation with 10% starch. According to Ahmad and Williams (1999), sucrose molecules with equatorial hydroxyl groups are associated with the amylose molecules and thereby prevent amylose–amylose interactions which favor more rigid gels. This explains the fact that with increasing sucrose content there is an increase in firmness of the gels.

Gels containing 12% of common variety starch and whey protein showed increase in firmness with increasing whey protein, but for formulation with 10% starch there is a small decrease, i.e., the highest starch concentration overcomes the inhibitory effect of whey protein due to the greater availability of amylose. Formulations with starch from the round root variety also showed a reduction of firmness. The increased concentration led to a higher amount of leached amylose, reducing the availability of

water in the medium, which favors the protein–protein interactions, leading to formation of less firm gels, how can be observed in formulations utilizing starch from the round root variety. In the formulations with starch from the common variety the amylose content is lower it is able to interact with water and proteins, where the lower number of protein–protein interactions leads to increased firmness of the gels.

In general, the increase in starch concentration led to a reduction in firmness of the gel for the control formulation of the common variety, due to the increased amount of amylose leached into the medium. The same effect cannot be observed for the round root variety, which may have occurred in function of increased syneresis and consequent increase in gel hardness. Sucrose in the concentrations studied led to increased stability of the gels formulated with the addition of whey protein concentrate, preventing the formation of segregated phases.

Rheological study

Frequency sweep

Variation of the storage (G') and dissipation moduli (G'') with the oscillatory frequency provides information on the viscoelastic character of the system. Gels in which $G' > G''$ are characterized as true or elastic gels and those with the opposite behavior ($G' < G''$) are characterized as viscous gels (Rao 2014).

For the frequency sweeps of gels (Fig. 3), a very small dependence of the G' values was observed with increase in frequency, while the values of G' were always greater than G'' . The higher the value of G' , greater is the solid character of the gel and the deformations are elastic or recoverable (Kavanagh and Ross-Murphy 1998; Rao 2014). It can be observed that with increasing starch concentration from 10 to 12% there was an increase in the elastic characteristics of the gels. Which can be explained by the fact that with increasing starch concentration there is a decrease in water availability in the medium and therefore the granules are not able to swell sufficiently, making them more rigid and more elastic. Gels formulated with starch from the round root variety without addition of sucrose and whey protein showed higher elasticity than gels formulated with starch from the same variety and supplemented with these components, because this starch has a lower swelling power and higher amylose content. The gels formulated with only starch of the common variety showed contrary behavior which was favored due to the greater swelling power of this starch and lower amylose content.

As the sucrose concentration increased and whey protein decreased there was a small increase in the elastic structure

(G') of the gels formulated with starch from the common variety. This fact can be explained because sucrose contributed to reduce swelling of the granules, making them more rigid and more elastic.

It can be observed that the sucrose and whey protein levels studied had a greater influence on gels formulated with starch from the round root variety, which is due to its higher amylose content. There was a reduction in elasticity of the gels formulated with 10% of this starch with sucrose concentrations of 1, 2 and 3% and whey protein levels of 4, 3 and 2% respectively; this behavior may have occurred due to increased protein levels in the gel formulations. With protein concentration increase there is a reduction in the elastic modulus of gels due to the formation of a weak matrix with regions of dispersed proteins (Aguilera and Rojas 1996). In the formulation containing 4% sucrose and 1% protein the sucrose had a stabilizing effect by binding with the amylose molecules which favored increased elasticity. This was also observed in the formulation containing 12% starch with the same levels of sucrose and whey protein.

The loss tangent or internal friction or damping ($\tan \delta$) is the ratio of energy lost per cycle and the energy stored during the cycle. This relationship is very useful in characterizing the gel strength. Thus, more rigid materials have lower $\tan \delta$ values, and likewise more flexible materials have higher $\tan \delta$ values. The gels presented viscoelastic behavior, with $\tan \delta$ values ranging from 0.001 to 3, where this behavior was observed in all gels studied (Fig. 4).

A decrease in the loss tangent values was observed with increasing sucrose levels for all gels with 12% starch, in agreement with the data related to the frequency sweep. Gels formulated with 1 and 2% sucrose showed no significant difference. Gels formulated with 12% of starch (control sample) were more flexible than others, which can be explained by the fact that the higher concentration reduced the availability of water and as a result there was not sufficient swelling of the starch granules.

The different levels of sucrose and whey protein influenced the complex viscosity of the gels studied, where the formulation containing 4% sucrose and 1% whey protein showed to be more viscous than the other formulations also supplemented with these components. The complex viscosity decreased with increase in frequency for all the gels studied. Thus, the pseudoplastic behavior of the gels is clear. The pseudoplastic gels have a behavior resultant of a fully organized structure formed of hydrogen bonds and polymer entanglement, which contributes to a high viscosity with low shear rates. With the increase in shear rate there occurs disaggregation of this network and consequently the viscosity is reduced.

The gels formulated with 10 and 12% starch of the round root variety, without addition of sucrose and whey

Fig. 3 Effect of protein concentrate and sucrose addition on the dynamic rheological properties of gels with 10% (**a**, **b**) and 12% (**c**, **d**) starch from arrowroot of common (**a**, **b**), round root (**b**, **d**) varieties during the frequency sweep. G' filled diamond and G'' open diamond: 0% sucrose and 0% protein concentrate; G' filled triangle and G''

open triangle: 1% sucrose and 4% protein concentrate; G' filled square and G'' open rectangle: 2% sucrose and 3% protein concentrate; G' filled circle and G'' open circle: 3% sucrose and 2% protein concentrate; G' filled star and G'' open star: 4% sucrose and 1% protein concentrate

protein, presented greater dynamic viscosity and consequently higher elasticity than the other formulations in accordance with Fig. 3 indicating that this formulation offered enhanced resistance to shear stresses.

Time sweep

For gels prepared with both starch varieties, the viscous component remained constant during the entire time while the elastic component showed a slight increase (Fig. 5). This effect was more pronounced for the gels formulated with starch of the round root variety of which reached G' values greater than gels of the common variety, indicating that gels made with this variety tend to retrograde more quickly than gels of the common starch. This is due to the fact that amylose retrogrades faster than amylopectin and has a strong tendency to reassociate by means of the formation of hydrogen bonds with other adjacent amylose molecules to form duplex crystal structures when the solution cools and remains for a long period of time (Bello-

Pérez et al. 2006). As a consequence of the retrogradation process water is lost by the starch granules and syneresis occurs. Thus, in a process of freezing and thawing the gels formulated with starch of the common variety would be more stable those formulated with starch of the round root variety.

The gels formulated with 10% starch of the round root variety (Fig. 5b) showed an increase of G' with increasing concentration of sucrose, indicating that increasing the sucrose content results in reduced tendency for the retrogradation process. Sucrose may have interacted with the water molecules resulting in their retention in the gels, which favored the more elastic gels. For gels formulated with 12% starch (Fig. 5c, d) it may be observed that there was a decrease in the storage modulus with increasing sucrose concentration. With an increase in starch concentration there is a reduced availability of water in the medium, therefore the starch granules swell to the point that they become more rigid and less deformable.

Fig. 4 Curves of $\tan(\delta)$ in function of frequency (Hz) of gels with 10% (a, b) and 12% (c, d) starch from arrowroot of common (a, b) and round root (b, d). Filled diamond: 0% sucrose and 0% protein concentrate; filled triangle: 1% sucrose and 4% protein concentrate;

filled square: 2% sucrose and 3% protein concentrate; filled circle: 3% sucrose and 2% protein concentrate; open circle with plus: 4% sucrose and 1% protein concentrate

Temperature sweep

Gels formulated with starch of the round root variety had higher gelatinization temperature (78–85 °C) than gels formulated with the common variety (75–80 °C). This fact may be explained because the round root presented a higher amylose content, and, as was seen in analysis of the swelling power, there are strong associative forces between amylose and amylopectin chains in this starch. These forces favor the increase in temperature required for swelling of the starch granules since more energy is necessary to break the intermolecular bonds to the starch granules interact with the water. Furthermore, the presence of sucrose and whey protein in the medium reduces the availability of water, which also favors the increase in gelatinization temperature.

Conclusion

Arrowroot starch of the common variety may be indicated for development of products that require firm consistency, due to its lower amylose content. Starch from the round root variety may be suitable for preparation of products that need to be firmer. The swelling power of gels formulated with starch of the common variety was greater than that of the round root variety and the solubility index had opposite behavior. Sucrose favored increased firmness of the gels studied, where gels of the common variety were firmer and whey protein led to decreased firmness except in gels formulated with 12% starch of the common variety.

Fig. 5 Effect of protein and sucrose addition on the dynamic rheological properties of gels with 10% (a, b) and 12% (c, d) starch from arrowroot of common (a, b) and round root (b, d) varieties submitted to 30 °C for 15 min. G' filled diamond and G'' open diamond: 0% sucrose and 0% protein concentrate; G' filled

triangle and G'' open triangle: 1% sucrose and 4% protein concentrate; G' filled square and G'' open rectangle: 2% sucrose and 3% protein concentrate; G' filled circle and G'' open circle: 3% sucrose and 2% protein concentrate; G' filled star and G'' open star: 4% sucrose and 1% protein concentrate

In the dynamic rheological test it was observed in the frequency sweeps that gels behave more like viscoelastic solids ($G' > G''$). The gels formulated with 12% starch were more elastic than the gels formulated with 10% starch. Both in the formulations with 10 and 12% starch, adding 4% sucrose and 1% protein resulted in greater gel elasticity.

The gels formulated with starch from the round root variety had higher gelatinization temperature than gels from common variety, since the high amylose content hampered granule swelling and required a more energy for swelling with a consequent increase in the gelatinization temperature.

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References

- Aguilera J, Rojas G (1996) Rheological, thermal and microstructural properties of heat-induced whey protein/starch gels. *J Food Sci* 62:1048–1053
- Ahmad FB, Williams PA (1999) Effect of sugars on the thermal and rheological properties of sago starch. *Biopolymers* 50(4):401–412
- Albano KM, Franco CML, Telis VRN (2014) Rheological behavior of Peruvian carrot starch gels as affected by temperature and concentration. *Food Hydrocolloids* 40:30–43
- AOAC INTERNATIONAL (1997) Official methods of analysis, 16th edn. AOAC International, Gaithersburg, pp 1–43
- Aprianita A, Vasiljevic T, Bannikova A, Kasapis S (2014) Physicochemical properties of flours and starches derived from traditional Indonesian tubers and roots. *J Food Sci Technol* 51(12):3669–3679
- Bello-Pérez LA, Montealvo MGM, Acevedo EA (2006) Almidón: definición, estructura y propiedades. In: Lajolo FM (eds) *Carboidratos em alimentos regionais ibero-americanos*. Edusp, São Paulo, pp 17–46

- BeMiller JN (2011) Pasting, paste, and gel properties of starch–hydrocolloid combinations. *Carbohydr Polym* 86(2):386–423
- Bligh EG, Dyer WJ (1959) A rapid method of total lipid extraction and purification. *Can J Biochem Phys* 37(8):911–917
- Charles AL, Cato K, Huang TC, Chang YH, Ciou JY, Chang JS, Lin HH (2016) Functional properties of arrowroot starch in cassava and sweet potato composite starches. *Food Hydrocolloids* 53:187–191
- Damodaran S, Parkin K, Fennema OR (2007) Fennema's food chemistry, 4th edn. CRC Press, Boca Raton
- Ferrari T, Leonel M, Sarmiento S (2005) Characteristics of the rhizomes and starch of arrowroot (*Maranta arundinacea*) harvested at different stages of development. *Braz J Food Technol* 8:93–98
- Gunaratne A, Hoover R (2002) Effect of heat–moisture treatment on the structure and physicochemical properties of tuber and root starches. *Carbohydr Polym* 49(4):425–437
- Hasjim J, Lee SO, Hendrich S, Setiawan S, Yongfeng A, Jane JJ (2010) Characterization of a novel resistant-starch and its effects on postprandial plasma-glucose and insulin responses. *Cereal Chem* 87(4):257–262
- Hernández-Medina M, Torruco-Uco JG, Chel-Guerrero K, Betancur-Ancona D (2008) Caracterización físico-química de almidones de tubérculos cultivados en Yucatán, México. *Food Sci Technol* 28(3):718–726
- Hitomi A, Hanjun T, Watanabe K, Mitsunaga T (2002) Some physicochemical properties of large, medium and small granule starches in fractions of wheat grain. *Food Sci Technol Res* 8(1):24–27
- Hoover R (2001) Composition, molecular structure, and physicochemical properties of tuber and root starches: a review. *Carbohydr Polym* 45(3):253–267
- Jyothi AN, Sajeev, Sreekumar JN (2010) Hydrothermal modifications of tropical tuber starches. I. Effect of heat–moisture treatment on the physicochemical, rheological and gelatinization characteristics. *Starch/Stärke* 62(1):28–40
- Kavanagh GM, Ross-Murphy SB (1998) Rheological characterisation of polymer gels. *Prog Polym Sci* 23(3):533–562
- Kumalasari ID, Harmayani E, Lestari LA, Raharjo S, Asmara W, Nishi K, Sugahara T (2012) Evaluation of immunostimulatory effect of the arrowroot (*Maranta arundinacea* L) in vitro and in vivo. *Cytotechnology* 64(2):131–137
- Leonel M, Sarmiento S, Cereda M, Guerreiro L (2002) Extraction and characterization of Biri starch (*Canna edulis*). *Braz J Food Technol* 5(1):27–32
- Martínez C (1989) Evaluación de la calidad culinaria y molinera del arroz. CIAT, Texas
- Moorthy SN (2002) Physicochemical and functional properties of tropical tuber starches: a review. *Starch/Stärke* 54(12):559–592
- Morris ER (1990) Mixed polymer gels. *Food gels*. Springer, Dordrecht, pp 291–359
- Mweta DE, Labuschagne MT, Bonnet S, Swarts J, Saka JD (2010) Isolation and physicochemical characterisation of starch from cocoyam (*Colocasia esculenta*) grown in Malawi. *J Sci Food Agric* 90(11):1886–1896
- Otegbayo B (2014) Effect of storage on the pasting characteristics of yam tubers. *Niger Food J* 32(2):113–119
- Parker R, Ring S (2001) Aspects of the physical chemistry of starch. *J Cereal Sci* 34(1):1–17
- Peroni F, Rocha T, Franco CML (2006) Some structural and physicochemical characteristics of tuber and root starches. *Food Sci Technol Int* 12(6):505–513
- Rao MA (2014) Measurement of flow and viscoelastic properties. *Rheology of fluid, semisolid, and solid foods: principles and applications*. Springer, Boston, pp 63–159
- Rocha TS, Demiate IM, Franco CMF (2008) Características estruturais e físico-químicas de amidos de mandioca-salsa (*Arracacia xanthorrhiza*). *Ciência Tecnol Alime* 28(3):620–628
- Spies RD, Hoseney RC (1982) Effect of sugars on starch gelatinization. *Cereal Chem* 59(2):128–131
- Şumnu G, Ndife M, Bayındırlı L (1999) Effects of sugar, protein and water content on wheat starch gelatinization due to microwave heating. *Eur Food Res Technol* 209(1):68–71
- Sweedman MC, Tizzotti MJ, Schäfer C, Gilbert RG (2013) Structure and physicochemical properties of octenyl succinic anhydride modified starches: a review. *Carbohydr Polym* 92(1):905–920
- Torre-Gutiérrez L, Chel-Guerrero LA, Betancur-Ancona D (2008) Functional properties of square banana (*Musa balbisiana*) starch. *Food Chem* 106(3):1138–1144
- Torruco-Uco J, Betancur-Ancona D (2007) Physicochemical and functional properties of makal (*Xanthosoma yucatanensis*) starch. *Food Chem* 101(4):1319–1326
- Van Hung P, Morita N (2005) Physicochemical properties and enzymatic digestibility of starch from edible canna (*Canna edulis*) grown in Vietnam. *Carbohydr Polym* 61(3):314–321