ELSEVIER

Food Chemistry 65 (1999) 339–346

Food Chemistry

Heat-moisture treatment effects on sweetpotato starches differing in amylose content

Lilia S. Collado, Harold Corke*

Cereal Science Laboratory, Department of Botany, The University of Hong Kong, Pokfulam Road, Hong Kong

Received 9 February 1998; received in revised form; accepted 28 September 1998

Abstract

Sweetpotato starch from two genotypes, Taiwan (15.2% amylose) and 93-006 (28.5% amylose), were exposed to heat-moisture treatment (HMT) of 25% moisture at 110°C for various exposure times at 'as-is' (pH 6.5–6.7) and alkaline pH (pH 10) conditions. In both starch samples at 'as-is' pH, there was a shift from a Type A pasting profile (characterized by a high to moderate pasting peak, major breakdown after holding time at 95°C and low cold paste viscosity) to a Type C pasting profile (characterized by lack of a pasting peak and no breakdown, with high cold paste viscosity in 93-006; and a slight breakdown in Taiwan). With HMT at pH 10, the pasting peak viscosity was increased and low hot paste viscosities and high cold paste viscosities were observed. Under both pH conditions after HMT, there were marked increases in gelatinization temperatures and broadening of the DSC gelatinization endotherms, and considerable decreases in swelling volume and solubilities. Gel textures of HMT starch samples appeared to be related to amylose content. Taiwan starch gel had a marked increase in hardness and adhesiveness, while that of 93-006 did not show significant differences in hardness after HMT. Both starch samples showed a marked reduction in resilience, indicating a shift from a long stringy nature to short paste consistency. Starch gels exposed to HMT under alkaline conditions showed a high degree of syneresis. © 1999 Elsevier Science Ltd. All rights reserved.

---

1. Introduction

Temperature and moisture contents during processing of starch are easily varied intentionally or unintentionally and can alter its functional properties. The term 'hydrothermal treatment' was used by Stute (1992) to describe physical modification of starch resulting from combinations of moisture and temperature conditions which affect its properties without visible changes in granule appearance. Physical modification of starch slurries in excess water at temperatures below gelatinization is referred to as annealing. Such conditions are often applied/encountered in the preparation of starches. Studies on annealing of wheat, corn, amaranth, oat, potato and lentil starches have been conducted (Hoover & Vasanthan, 1994; Jacobs, Eerlingen, Clauwaert, & Delcour, 1995; Knutson, 1990; Krueger, Knutson, Inglett, & Walker, 1987; Larsson & Eliasson, 1991; Paredes-Lopez, Schevenin, Hernandez-Lopez, & Carabez-Trejo, 1989; Stute, 1992; Yost & Hoseney, 1986).

In contrast, heat-moisture treatment (HMT), refers to the exposure of starch to higher temperatures, commonly above the gelatinization temperature, at very restricted moisture content (18–27%). Studies have been conducted on corn, cassava, wheat, oat, barley, triticale and lentil starches (Abraham, 1993; Donovan, Lorenz, & Kulp, 1983; Hoover & Manuel, 1996; Hoover & Vasanthan, 1994; Kulp & Lorenz, 1981; Kurakake, Tachibana, Masaki, & Komaki, 1996; Maruta et al., 1994; Sair, 1964; Stute, 1992). The general effects of hydrothermal treatments are increased gelatinization temperatures, and changes in gelatinization range (narrowing or broadening of the DSC endotherms), X-ray diffraction patterns, swelling volume and solubility, with consequent changes in functionality.

Early work on hydrothermal treatments was done on potato starch intended to replace corn in times of shortage (Stute, 1992). Abraham (1993) noted that HMT cassava starch had excellent freeze-thaw stability and could be used in pie filling with good organoleptic properties. Lorenz and Kulp (1981) found that HMT improved the bread and cake baking quality of potato starch but decreased that of wheat starch. In many

---

* Corresponding author. Tel.: +852-2857-8522; Fax: +852-2857-8521; E-mail: harold@hku.hk

PII: S0308-8146(98)00228-3

Asian foods, an alkali (often termed '*kansui*') is added for the development of desirable color and texture such as in Cantonese noodles (Moss, Miskelly, & Moss, 1986) as well as to neutralize acids from fermentation, as in the case of steamed bread (Ding & Zheng, 1991; Huang & Miskelly, 1991), and rice cakes (Juliano, 1993; Juliano & Sakurai, 1983). In a survey of starch pearls from Hong Kong, Singapore and the Philippines, a wide range of pH was observed (Collado & Corke, 1998), and it seems that high pH is beneficial to the formation of the starch pearl structure.

The aim of this study was to determine the effect of HMT under 'as-is' pH (6.5–6.7) and alkaline (pH 10) conditions on sweetpotato starch pasting properties, gelatinization temperature, swelling volume, solubility and gel texture.

2. Materials and methods

2.1. Samples

Starch was purified from two genotypes of sweetpotato obtained from the International Potato Center, Philippines, as in Collado and Corke (1997). The two genotypes, Taiwan and 93-006, had starches of different amylose contents (15.2 and 28.5%, respectively) and differed in pasting profiles.

2.2. Heat-moisture treatment

For HMT in water, the samples were adjusted to 25% moisture, equilibrated at 4–5°C overnight, and placed in a covered Petri dish for 4, 8 and 16 h at 110°C. The samples were shaken occasionally for even distribution of heat. For HMT under alkaline conditions, the starch was mixed with *kansui* solution (9:1 Na_2CO_3: K_2CO_3) adjusted to give 25% moisture content and 1% *kansui* concentration based on starch weight. Samples were then equilibrated and treated as for the water treatment. After HMT, the starches were dried at 50°C overnight. Untreated samples were used as controls.

2.3. Analytical methods

2.3.1. Pasting properties

A Rapid Visco-Analyzer Model 3-D (RVA) (Newport Scientific Pty Ltd., Warriewood, Australia) was used to determine RVA viscoamylographs of the samples at 11% starch concentration. 3.0 g starch (14% m.b.) was mixed with distilled water to make a total weight of 28 g in the RVA sample canister. A programmed heating and cooling cycle was used at constant shear rate, where the sample was held at 50°C for 1 min, heated to 95°C in 7.5 min, held at 95°C for 5.5 min, cooled to 50°C in 7.5 min, and then held at 50°C for 5 min. Duplicate tests were used in each case. Peak viscosity (PV), time to reach PV (P_{time}), temperature at PV (P_{temp}), hot paste viscosity or viscosity after the holding time at 95°C (HPV), and cool paste viscosity or the viscosity at the end of the hold time at 50°C (CPV) were recorded.

2.3.2. Swelling volume

Swelling volume (Crosbie, 1991) was determined by weighing 0.35 g (d.b.) sweetpotato starch into 125×16 mm Pyrex tubes to which 12.5 ml of water was added. The tubes were equilibrated at 25°C for 5 min, transferred to a 92.5°C waterbath and mixed in a prescribed schedule for 30 min. Samples were cooled in ice water for 1 min, placed in a 25°C bath for 5 min and centrifuged at 1000 ***g*** for 15 min. The height of the gel was measured and converted to volume of gel per unit dry weight of the sample. An aliquot of supernatant was analyzed for total carbohydrate content by the phenol-sulfuric method (Dubois, Gilles, Hamilton, Rebers, & Smith, 1956).

2.3.3. Starch gel texture

Texture Profile Analysis (TPA) was done on the starch gel after the RVA viscoamylograph determination. The RVA paddle was removed and the canister was covered with Parafilm™. The gel set at room temperature (RT) (20–22°C); then it was stored at 4°C overnight and equilibrated at RT for 4 h. A texture profile analysis with fracture was done to a distance of 10 mm at a speed and post speed of 1 mm/s using a 5 mm diameter Bakelite® cylindrical probe, using a TA-XT2 texture analyzer (Stable Micro Systems, Godalming, UK). Hardness, adhesiveness and resilience were recorded. Hardness is defined as the maximum force (g), and adhesiveness (gs) as the area of the negative curve as the probe moves back to initial position. Resilience is the positive area as the probe returns to original position over the area of curve as the probe moves to target distance in the gel [Fig. 4(A), (B), see below]. The 5 mm probe was chosen from prior experience to give an indication of both adhesiveness and fracture behavior of the material such as may be experienced in biting, and is related to the properties of major products such as sweetpotato starch noodles, that are expected to be made from these starches.

2.3.4. Thermal characteristics

Gelatinization characteristics were determined with a Mettler DSC-20 Differential Scanning Calorimeter (Mettler-Toledo AG Instruments, Naenikon-Uster, Switzerland). Starch samples (2.5 mg, d.b.) were placed in aluminum crucibles; distilled water was added to make a 1:3 (w/w) starch:water, mix, and the crucible was sealed. The gelatinization peak temperature (T_p, °C) and enthalpy (ΔH, J/g) were determined.

2.3.5. *Statistical analysis*

All analyses were done in duplicate. Analysis of variance was performed to calculate significant differences in treatment means, and LSD ($p<0.05$) was used to separate means (SAS, 1988).

3. Results and discussion

3.1. *Pasting properties*

The RVA viscoamylograph of native Taiwan starch under 'as-is' pH condition, was a Type A pasting profile (as defined by Schoch & Maywald, 1968) characterized by a high PV (430 RVU), with high breakdown and low CPV (278 RVU). After HMT, there was a marked decrease in the PV (268 RVU), a very slight breakdown, and an increase in CPV (385 RVU), more like a Type C pasting profile. The same trend was observed with 8 h HMT exposure but, with 16 h, a lower PV, low HPV and low CPV resulted [Table 1, Fig. 1(A)]. This contrasted with the result in 93-006 where, after exposure to HMT for 4 to 16 h, there was no definable PV and breakdown, and the CPV increased from 255 RVU in the untreated sample to 555 RVU with 16 h HMT exposure [Table 1, Fig. 1(B)].

With hydrothermal treatments, whether done in excess water (starch suspension) or below 30% (no free water), the general effect on pasting properties is lower peak viscosities, less breakdown and higher cold paste viscosities for potato starch (Stute, 1992). However, Jacobs et al. (1995) found that changes in pasting properties, after annealing at 3–4°C lower than gelatinization temperature for 24 h, were different in starches from different botanical sources. Potato starch had lower peak viscosities and higher cold paste viscosities while wheat and rice starches had higher peak viscosities and cold paste viscosities. In the case of HMT, there was a consistent decrease of Brabender pasting viscosities at 95°C after 30 min holding time as observed for normal maize, amylomaize (Hoover & Manuel, 1996), potato (Hoover & Vasanthan, 1994; Kulp & Lorenz, 1981; Stute, 1992), oat, lentil, yam starches (Hoover &

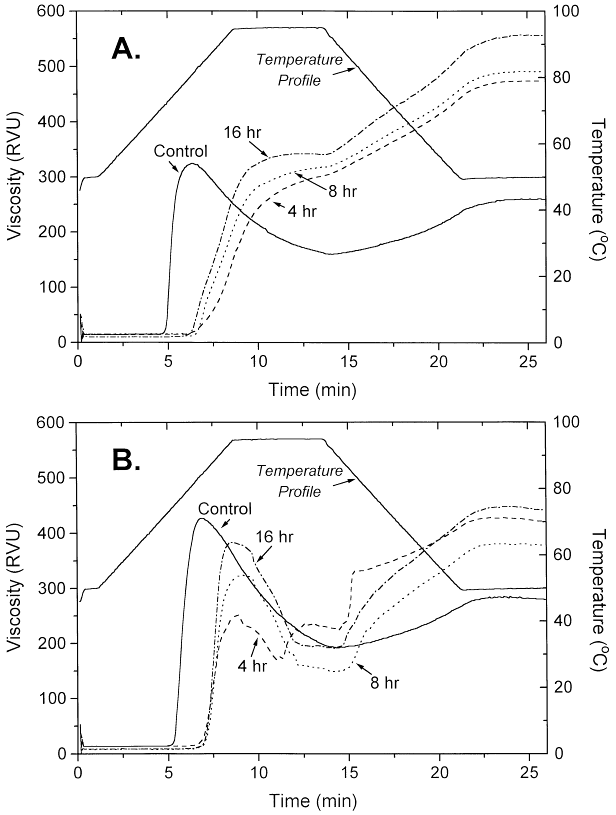

Fig. 1. The RVA viscoamylograph of sweetpotato starch from genotype Taiwan before and after heat-moisture treatment at different exposure times: (A) under 'as-is' pH; (B) at pH 10. RVU—rapid viscosity units.

Table 1
The mean RVA pasting parameters of 11% starch concentration from sweetpotato starch exposed to heat moisture treatment under different pH conditions

Taiwan	'As-is' pH					pH 10				
Time (h)	PV (RVU)	P_{time} (min)	P_{temp} (°C)	HPV (RVU)	CPV (RVU)	PV (RVU)	P_{time} (min)	P_{temp} (°C)	HPV (RVU)	CPV (RVU)
0	430 a	6.8 b	83.9 c	196 b	278 c	461 a	7.1 d	85.5 c	143 d	344 d
4	268 b	10.0 a	95.0 a	256 ab	385 b	269 d	10.0 a	94.9 a	174 b	399 b
8	301 c	10.0 a	95.0 a	283 a	405 a	324 c	9.1 b	94.7 a157 c	380 c	
16	236 d	8.1 b	91.5 b	164 b	232 d	381 b	8.5 c	93.7 b	197 a	440 a
93-006	'As-is' pH					pH 10				
Time (h)	PV (RVU)	P_{time} (min)	P_{temp} (°C)	HPV (RVU)	CPV (RVU)	PV (RVU)	P_{time} (min)	P_{temp} (°C)	HPV (RVU)	CPV (RVU)
0	321	6.4	80.9	160 d	255 c	490 a	7.5 d	87.4 c	154 c	427 b
4	–	–	–	306 c	478 b	254 c	9.6 b	94.9 ab	151 c	382 c
8	–	–	–	320 b	496 b	264 c	10.0 a	94.9 b	170 b	399 d
16	–	–	–	346 a	555 a	373 b	8.9 c	94.5 b	184 a	481 a

Means with the same letter in a column within each genotype are not significantly different ($p<0.05$). RVU—rapid viscosity units.

Vasanthan) and cassava (Abraham, 1993). However pasting properties of waxy maize seemed to be unaffected by HMT (Hoover & Manuel, 1996).

Hydrothermal treatment may make the granules resistant to deformation by strengthening the intragranular binding forces (Stute, 1992), and it was speculated that, in annealed starch, swollen gelatinized granules were more rigid, contributing significantly to high cold paste viscosities. Annealed and native starch, when pasted in dimethyl sulfoxide (DMSO), gave the same cold paste viscosities (Jacobs et al., 1995). The significant contribution of swollen granules to the viscosity of the starch paste is clearly seen in waxy potato starch, which does not form swollen granules upon gelatinization and immediately transforms into a macromolecular solution which is long and stringy with a very low viscosity. In normal potato starch, overcooking at higher temperatures than gelatinization (120°C) is needed to remove remnants of the swollen granules and viscosity is drastically reduced (Hermansson & Svegmark, 1996).

Under alkaline conditions, HMT had a different effect on the pasting profile. The short exposure time, 4 h, effected a lower peak viscosity but as exposure time was increased, higher PV was observed [Table 1, Figs. 1(B) and 2(B)]. The alkaline condition gave a free swelling nature to the native starch but had a more pronounced effect on 93-006 which had lower PV in the native starch than with Taiwan which originally had high PV.

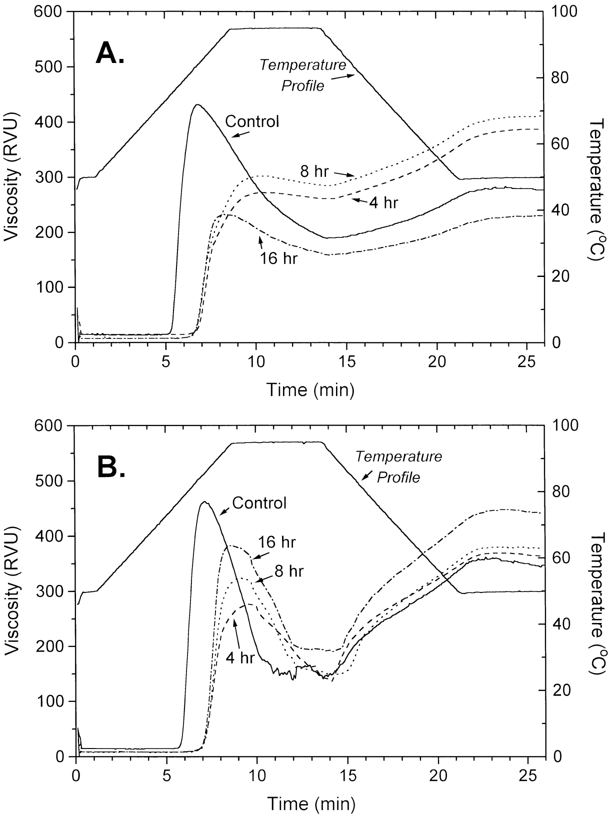

Fig. 2. The RVA viscoamylograph of sweetpotato starch from genotype 93-006 before and after heat moisture treatment at different exposure times: (A) under 'as-is' pH; (B) at pH 10. RVU—rapid viscosity units.

The pasting profiles of the HMT samples under alkaline condition were similar to the pasting profiles of milled starch pearls with high pH (Collado & Corke, 1998). It was also similar to the pasting profile of Amylomaize I (13–15% starch concentration) pasted in 0.1 N NaOH which showed a high peak viscosity and extensive breakdown on cooking that resembled that of potato starch in water (Pomeranz, 1991) and which also showed high cold paste viscosity on cooling. It appears that, under alkaline conditions, only short periods of exposure to high temperature, as in the process of making starch pearls, is needed to attain this effect. In making starch pearls, the granulated starch (~50% moisture) is roasted from 120–180°C in open pans or mechanical roasters for 8 to 10 min (Varadharaju, Balasubramanian, & Parvathy, 1992).

3.2. *Thermal properties*

An increase in gelatinization temperature was observed for the starches exposed to HMT under both pH conditions in both genotypes (Table 2, Fig. 3). The mean T_p of the untreated samples was 75.2°C for Taiwan and 70.9°C for 93-006, but the T_p for Taiwan increased to 78.1°C while that of 93-006 increased to 79.9°C under alkaline conditions. Under HMT for 4 h the T_p further increased to 84.3°C in Taiwan and 81.3°C in 93-006 ('as-is' pH), and to 84.0°C in Taiwan and 86.8°C in 93-006 (pH 10). Further increase in exposure time under 'as-is' and pH 10 conditions did not significantly change the T_p except that a significant

Table 2

The mean gelatinization peak, T_P°C and enthalpy, ΔH, (J/g) of sweetpotato genotypes Taiwan and 93-006 exposed to heat moisture treatment in water and in alkaline conditions

Taiwan	'As-is' pH		pH 10	
Time (h)	T_P	ΔH	T_P	ΔH
0	75.2 c	11.6 a	78.1 c	17.7 a
4	84.3 a	13.2 a	84.0 b	13.6 b
8	84.3 a	13.5 a	85.0 a	12.2 b
16	83.6 b	13.1 a	85.0 a	11.9 b
93-006	'As-is'		pH 10	
Time (h)	T_P	ΔH	T_P	ΔH
0	70.9 b	9.8 a	79.9 b	11.7 ab
4	81.3 a	10.9 a	86.8 a	10.6 b
8	82.1 a	11.9 a	86.8 a	12.6 ab
16	81.8 a	12.9 a	87.8 a	13.9 a

Means with the same letter in a column within each genotype are not significantly different ($p < 0.05$).

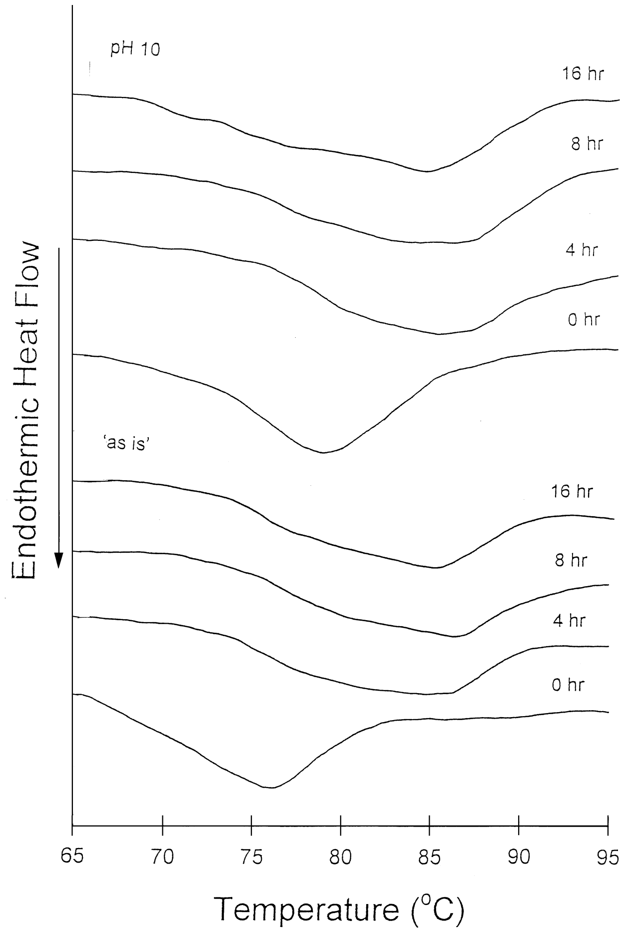

Fig. 3. Differential Scanning Calorimeter (DSC) gelatinization endotherms of sweetpotato starch from genotype 93-006 before and after heat-moisture treatment at different exposure time under 'as-is' pH and pH 10.

decrease was observed in Taiwan after 16 h HMT. In control starches, the ΔH increased substantially in Taiwan as the pH was raised but only slightly in 93-006 (Table 2). ΔH had a non-significant increase as the starches were exposed to HMT ('as-is' pH), but in the case of Taiwan (pH 10) there was a decrease in ΔH after exposure to HMT. However, the ΔH for 4 to 16 h exposure time was not significantly different. For 93-006, the ΔH under the two pH conditions did not differ significantly from the untreated samples. There was an increase in the broadness of the gelatinization endotherm with HMT in both pH conditions (Fig. 2). A broader gelatinization range at higher temperature was also observed for wheat, potato (Kulp & Lorenz, 1981), normal and amylomaize starches (Hoover & Manuel, 1996). The increase in gelatinization range differs by botanic source. A greater increase in gelatinization range was observed in potato starch compared to wheat starch (Kulp & Lorenz). Furthermore, the gelatinization temperature range of waxy maize starch is not affected by annealing (Stute, 1992) nor by HMT (Hoover & Manuel).

For annealed starches a narrowing of the gelatinization temperature was observed at higher temperature (Jacobs et al., 1995; Larsson & Eliasson, 1991). Stute (1992) pointed out that the alterations in the DSC curve are sensitive indicators of the type of hydrothermal treatment the starch has undergone. For annealed starches, the narrower peaks indicated greater homogeneity during melting of crystallites and the swelling and hydration of starch granules. The important factors determining the sharpness of the peak are high levels of water and an amorphous phase (Stute, 1992; Zobel, 1992). Marchant and Blanshard (1978) described annealing broadly as a condition in which granules assume a more stable configuration. This is viewed as the realignment of polymer chains within the non-crystalline regions of the granule as well as in the crystallites (Zobel) or change in the coupling forces between the crystallites and the amorphous matrix (Stute).

On the other hand, the broadening of the gelatinization endotherms could be viewed with reference to other DSC studies (as in the case of Näegeli dextrins in Donovan & Mapes, 1980), as deriving from granular starch, which through gradual erosion of the amorphous phase by acid, led to increased crystallinity, resulting in broadening of the DSC peak (Stute, 1992; Zobel, 1992). The endotherm was interpreted as revealing the intrinsic stability and heterogeneity in size and perfection of crystalline regions in granular starches (Zobel). Starch-chain associations within the amorphous regions and the degrees of crystalline order are altered during HMT. The magnitude of these changes are dependent on the moisture content during heat treatment and on the starch source (Hoover & Vasanthan, 1994).

3.3. Swelling volume and solubility

Under HMT, the swelling volume of starch decreased from 32.3 to 13.0 ml/g in Taiwan and from 28.0 to 13.0 ml/g in 93-006 ('as-is' pH) after 16 h exposure. Under alkaline conditions, the swelling volume of Taiwan increased to 33.7 ml/g and 93-006 increased to 29.3 m/g (Table 3). Under both pH conditions there was a considerable decrease in solubility. Slightly higher solubilities were observed for the heat–moisture treated samples under alkaline conditions than at 'as-is' pH.

Lower swelling factors and amylose leaching were observed by Hoover, Vasanthan, Senanayake, and Martin (1994) in HMT wheat, oat, lentil and potato starches. Potato starch showed the greatest decrease in swelling factor compared to oat and wheat starches, but wheat, oat and potato starches showed similar amylose leaching properties after HMT. However, increased solubilities were observed in wheat and corn starch

Table 3
The mean swelling volume (SV) and solubilities of the sweetpotato starch exposed to heat moisture treatment at 'as-is' pH and at pH 10

Taiwan	'As-is' pH		pH 10	
Time (h)	SV (ml/g)	Solubility %	SV (ml/g)	Solubility %
0	32.3 a	14.6 a	33.7 a	26.8 a
4	13.8 b	10.9 b	13.8 b	14.0 b
8	13.0 c	11.2 b	14.0 b	13.4 c
16	13.0 c	11.1 b	13.8 b	13.6 c
93-006	'As-is' pH		pH 10	
Time (h)	SV (ml/g)	Solubility %	SV (ml/g)	Solubility %
0	28.0 a	14.7 a	29.3 a	21.7 a
4	13.0 b	11.0 c	13.4 b	12.2 b
8	13.0 b	11.0 c	13.6 b	11.8 c
16	13.0 b	11.5 b	13.4 b	12.3 b

Means with the same letter in a column within each genotype are not significantly different ($p < 0.05$).

Table 4
Textural attributes of starch gels from two sweetpotato genotypes, Taiwan and 93-006, exposed to heat moisture treatment at 'as-is' pH condition

Taiwan			
Time (h)	Hardness (g)	Adhesiveness (gs)	Resilience ratio
0	18.1 d	−18.6 a	0.29 a
4	27.9 c	−40.3 b	0.05 b
8	34.7 b	−47.4 b	0.06 b
16	42.4 a	−70.9 c	0.06 b
93-006			
Time (h)	Hardness (g)	Adhesiveness (gs)	Resilience ratio
0	34.7 a	−41.0 a	0.14 a
4	32.9 a	−44.0 a	0.09 b
8	31.7 a	−44.8 a	0.07 b
16	32.6 a	−61.2 b	0.08 b

exposed to HMT (Kurakake et al., 1996; Kulp & Lorenz, 1981).

3.4. Texture of starch gel

A starch gel is a solid–liquid system having a continuous network in which the liquid phase is entrapped. Free amylose molecules form hydrogen bonds not only with one another but also with amylopectin branches extending from swollen granules, so the granules are part of the solid continuous network (Penfield & Campbell, 1990). The presence of amylose in the continuous phase will result in the formation of a strong gel on cooling. From mixed amylose–amylopectin model systems it was shown that amylopectin forms a continuous phase below 22% amylose (Hermansson & Svegmark, 1996). This may have contributed to the difference in response of the two genotypes to the HMT in terms of the texture of the starch gel.

In the untreated samples, for Taiwan (15.2% amylose) the continuous phase in the starch gel should be amylopectin, while for 93-003 (28.5% amylose), the continuous phase should be amylose. This would account for the great difference in the texture of the untreated starch gels (Table 4). The starch gel from 93-006 was much harder (34.7 g) than that of Taiwan (18.1 g). However, after HMT, a great increase in hardness was observed in the starch gel from Taiwan, but not from 93-006 where the hardnesses of the treated and untreated samples were not significantly different. Theoretically, an increase in amylose leaching and decrease in swelling factor would increase gel firmness. Highly swollen granules occurring between adjacent amylose chains would hinder their association during retrogradation. In potato starch (Hoover & Vasanthan, 1994), where a great increase in gel firmness was observed, the large decrease in swelling factor negates the decrease in amylose leaching. Such may have also been the case in the observed increased hardness of the starch gels from HMT sweetpotato starch. Likewise, the rigidity of the granular structure or 'ghost' as postulated by Jacobs et al. (1995) is also consistent with these findings.

Under near neutral pH, Taiwan starch after HMT showed increasing gel hardness, while 93-006 seemed to be less affected. A general effect of HMT was great loss of resilience [Fig. 4(A),(B)]. Under alkaline conditions, the gels had a greater tendency for retrogradation and once the gel was touched by the probe the gel broke with release of water. The starch gels from the longest exposure time under alkaline HMT showed clear separation from the liquid after overnight storage. This was not observed in starch gels exposed to HMT under 'as-is' pH. Apparently storage at 4–5°C resulted in lower energy levels which triggered further hydrogen bonding. The gel structure is tightened and the water-holding capacity is decreased (Penfield & Campbell, 1990).

Depending on the intended use, HMT could diversify the utilization of root crops. We will discuss two products produced from sweetpotato starch: starch noodles (Collado & Corke, 1997; Jeong, 1992; Quach, 1992; Wang, Song, & Zhang, 1995) and starch pearls (Collado & Corke, 1998), where swelling, solubility and retrogradation are critical for the quality of the product. These products involve at least two heating processes before they are consumed, the first being critical to the formation of the structure of the intermediate product. The conditions for granulation of starch in the production of starch pearls (Magda, 1993; Raja, Abraham, Sreemulanathan, & Mathew, 1979), and the preparation of starch noodles (Timmins, Marter, Westby, & Rickard, 1992; Wang et al. 1995; Jin, Wu, & Wu, 1994) may be

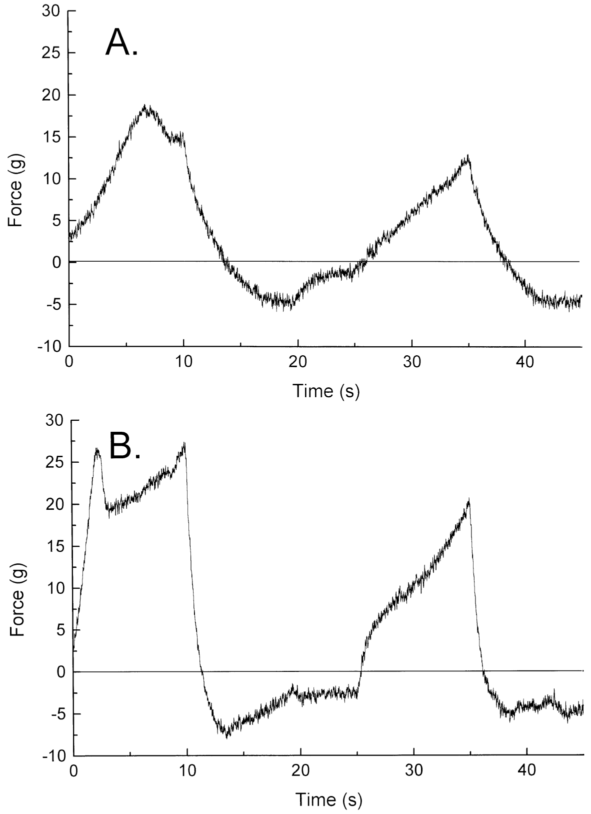

Fig. 4. Texture profiles of sweetpotato starch at 11% starch concentration from the genotype Taiwan (A) before and (B) after 4 h exposure to heat moisture treatment.

considered a closed-packed system (~50% moisture content). A closed-packed system is obtained if the granules have high swelling capacity or if starch concentration is very high. At very high starch concentrations, there will be insufficient water to gelatinize all the granules. The most important effect of close-packing is that the leaching of amylose out of the granules will be restrained. If amylose remains inside the swollen granules, it cannot form a continuous gel phase outside the granules (Hermansson & Svegmark, 1996).

Furthermore, the heating times for gelatinization of starch for the two products are short but under very different conditions. The starch pearls are roasted (dry heat) at 120–180°C (Varadharaju et al., 1992) for 8–10 min and then further dried to 10% moisture by a stream of hot air. Starch noodles are boiled or steamed (moist heat) for 3–5 min (Timmins et al., 1992), immersed in cold water for 3–5 min, chilled at refrigeration temperature and then finally air-dried. After boiling in water, both processes result in a translucent gummy gelled product. In mungbean starch noodles and tapioca starch pearls, micelles of retrograded amylose form a structural network that resists disintegration during cooking (Mestres, Colonna, & Buleon, 1988; Xu & Seib, 1993).

For starch noodles, the best substrates are those with higher than 30% amylose content (Galvez, Resurreccion, & Ware, 1994; Jin et al., 1994; Juliano, 1993; Lii & Chang, 1981) which exhibit a type C Brabender Viscoamylogram and high rate of retrogradation. It is interesting to note that, under small to large scale production, sweetpotato starch is exposed to various forms of hydrothermal treatments. Sometimes, starch noodles are produced directly from the wet-milled starch under small scale production, while others are produced from sun-dried starch at cooperative village-level production. Furthermore, in large scale operations, blast spray driers are used where the starch is dried in split seconds under temperatures greater than 100°C (Wheatley, personal communication).

In the case of starch pearls, a free swelling starch is required to partially gelatinize and exude amylose under the short exposure time to high temperature during roasting and set a good surface finish (Collado & Corke, 1998; Xu & Seib, 1993). There is sufficient evidence to prove that adjustment of pH by the addition of alkali during pearling could promote this functionality, resulting in a smooth surface of the starch pearl. A high tendency to retrograde as seen in the starch gels from alkaline HMT starch may also hasten the setting of the surface. Acidic starch pearls had rougher surfaces and higher percentages of broken beads.

The effects of the various combinations of temperatures and moisture content to which the starch is intentionally or unintentionally exposed should be more thoroughly studied to identify conditions for the development of favorable starch functionality for the intended end use. Understanding of the interaction of genotype and processing effects is essential to be able to understand or model the effects of HMT on sweetpotato and other starches. Further, an understanding of the basic process of manufacture, including various thermal effects, of traditional starch-based foods is essential in order to enable design of appropriate scale-up technologies.

Acknowledgements

The authors thank Dr. Christopher C. Wheatley, Processing Specialist for East Asia, Southeast Asia-Pacific Region, International Potato Center, Bogor, Indonesia, for his valuable suggestions and continuous support. Financial support was received from the University of Hong Kong Committee on Research and Conference Grants, and the Research Grants Council of Hong Kong.

References

Abraham, T. E. (1993). Stabilization of paste viscosity of cassava by heat moisture treatment. *Starch/Staerke, 45*, 131–135.

Collado, L. S., & Corke, H. (1997). Properties of starch noodles as affected by sweet potato genotype. *Cereal Chemistry, 74*, 182–187.

Collado, L. S., & Corke, H. (1998). Pasting properties of commercial and experimental starch pearls. *Carbohydrate Polymers, 35*, 89–96.

Crosbie, G. B. (1991). The relationship between starch swelling properties, paste viscosity and boiled noodle quality in wheat flours. *Journal of Cereal Science, 13*, 145–150.

Ding, X. L., & Zheng, J. X. (1991). Steamed bread and noodles in China. In D. J. Martin, & C. W. Wrigley (Eds.), *Cereals International: Proceedings of the 41st Australian Cereal Chemistry Conference*, Brisbane, Australia. Parkville, Australia: Royal Australian Chemical Institute.

Donovan, J. W., Lorenz, K., & Kulp, K. (1983). Differential scanning calorimetry of heat-moisture treated wheat and potato starches. *Cereal Chemistry, 60*, 381–387.

Donovan, J. W., & Mapes, C. J. (1980). Multiple phase transitions of starches and Naegeli amylodextrins. *Starch/Staerke, 32*, 190–193.

Dubois, M., Gilles, K. A., Hamilton, J. K., Rebers, P. A., & Smith, F. (1956). Colorimetric method for determination of sugars and related substances. *Analytical Chemistry, 28*, 350–356.

Galvez, F. C. F., Resurreccion, A. V. A., & Ware, G. O. (1994). Process variables gelatinized starch moisture effects on physical properties of mungbean noodles. *Journal of Food Science, 59* (386), 378–381.

Hermansson, A. M., & Svegmark, K. (1996). Developments in the understanding of starch functionality. *Trends in Food Science and Technology, 7*, 345–353.

Hoover, R., & Manuel, H. (1996). The effect of heat-moisture treatment on the structure and physicochemical properties of normal maize, waxy maize, dull waxy maize and amylomaize V starches. *Journal of Cereal Science, 23*, 153–162.

Hoover, R., & Vasanthan, T. (1994). Effect of heat-moisture treatment on the structure and physicochemical properties of cereal, legume, and tuber starches. *Carbohydrate Research, 252*, 33–53.

Hoover, R., Vasanthan, T., Senanayake, N. J., & Martin, A. M. (1994). The effects of defatting and heat-moisture treatment on the retrogradation of starch gels from wheat, oat, potato and lentil. *Carbohydrate Research, 261*, 13–24.

Huang, S. D., & Miskelly, D. M. (1991). Steamed bread—a popular food in China. Food Australia *43*, 346–347, 350–351.

Jacobs, H., Eerlingen, R. C., Clauwaert, W., & Delcour, J. A. (1995). Influence of annealing on the pasting properties of starches from varying botanical sources. *Cereal Chemistry, 72*, 480–487.

Jeong, B. C. (1992). Sweetpotato processing, marketing and utilization in Korea. In G. J. Scott, S. Wierman, & P. I. Ferguson (Eds.), *Product development for root and tuber crops, Vol. 1. Asia*. Lima, Peru: International Potato Center (CIP).

Jin, M., Wu, J., & Wu, X. (1994). A study on properties of starches used for starch noodle making. In G. Xie, & Z. Ma (Eds.), *Proceedings of the 1994 international symposium and exhibition on new approaches in the production of food stuffs and intermediate products from cereal grains and oil seeds* (pp. 488–496). Beijing, China: CCOA/ICC/AACC.

Juliano, B. O. (1993). Major processed rice products. In *Rice in human nutrition*. (pp. 101–123). FAO food and nutrition series, No. 26. Rome, Italy: Food and Agriculture Organization.

Juliano, B. O., & Sakurai, J. (1983). Miscellaneous rice products. In B. O. Juliano (Ed.), *Rice Chemistry and Technology*, (pp. 570–628) St. Paul, MN: American Association of Cereal Chemists.

Knutson, C. A. (1990). Annealing of maize starches at elevated temperatures. *Cereal Chemistry, 67*, 376–384.

Krueger, B. R., Knutson, C. A., Inglett, G. E., & Walker, C. E. (1987). A differential scanning calorimetry study on the effect of annealing on gelatinization behavior of corn starch. *Journal of Food Science, 52*, 715–718.

Kulp, K., & Lorenz, K. (1981). Heat-moisture treatment of starches. I. Physicochemical properties. *Cereal Chemistry, 58*, 46–48.

Kurakake, M., Tachibana, Y., Masaki, K., & Komaki, T. (1996). Adsorption of alpha-amylase on heat-moisture treated starch. *Journal of Cereal Science, 23*, 163–168.

Larsson, I., & Eliasson, A. C. (227). Annealing of starch at an intermediate water content. *Starch/Staerke, 43*.

Lii, C. Y., & Chang, S. M. (1981). Characterization of red bean (*Phaseolus radiatus* var. *aurea*) starch and its noodle quality. *Journal of Food Science, 46*, 78–81.

Lorenz, K., & Kulp, K. (1981). Heat-moisture treatment of starches. II. Functional properties and baking potential. *Cereal Chemistry, 58*, 49–52.

Magda, R. R. (1993). Sago from palms. *Food Marketing and Technology, 7*, 14–15.

Marchant, J. L., & Blanshard, J. M. V. (1978). Studies of the dynamics of the gelatinization of starch granules employing a small angle light scattering system. *Starch/Staerke, 30*, 257–264.

Maruta, I., Kurahashi, Y., Takano, R., Hayashi, K., Yoshino, Z., Komaki, T., & Hara, S. (1994). Reduced-pressurized heat-moisture treatment: a new method for heat-moisture treatment of starch. *Starch/Staerke, 46*, 177–181.

Mestres, C., Colonna, P., & Buleon, A. (1988). Characteristics of starch networks within rice flour noodles and mungbean starch vermicelli. *Journal of Food Science, 53*, 1809–1812.

Moss, H. J., Miskelly, D. M., & Moss, R. (1986). The effect of alkaline conditions on the properties of wheat flour dough and Cantonese-style noodles. *Journal of Cereal Science, 4*, 261–268.

Paredes-Lopez, O., Schevenin, M. L., Hernandez-Lopez, D., & Carabez-Trejo, A. (1989). Amaranth starch—isolation and partial characterization. *Starch/Staerke, 41*, 205–207.

Penfield, M. P., & Campbell, A. D. (1990). Starch. In *Experimental Food Science*. (3rd ed., pp. 358–381). San Diego, CA: Academic Press.

Pomeranz, Y. (1991). *Functional properties of food components*. (2nd ed., pp. 2–78). San Diego, CA: Academic Press.

Quach, N. (1992). Cassava and sweetpotato processing, marketing and utilization in Vietnam. In G. J. Scott, S. Wiersema, & P. I. Ferguson (Eds.), *Product development for root and tuber crops, vol. 1. Asia* (pp. 67–77). Lima, Peru: International Potato Center (CIP).

Raja, K. C. M., Abraham, E., Sreemulanathan, H. H. S., & Mathew, A. G. (1979). Chemistry and technology of cassava. *Indian Food Packer, 33*, 31–43.

Sair, L. (1964). Heat-moisture treatment of starches. In R. L. Whistler (Ed.), *Methods in carbohydrate chemistry* (pp. 283–284). New York: Academic Press.

SAS (1988). SAS/STAT Users Guide, Release 6.03. SAS Institute Inc., Carey, NC.

Schoch, T. J., & Maywald, E. C. (1968). Preparation and properties of various legume starches. *Cereal Chemistry, 45*, 546–573.

Stute, R. (1992). Hydrothermal modification of starches: the difference between annealing and heat moisture treatment. *Starch/Staerke, 6*, 205–214.

Timmins, W. H., Marter, A. D., Westby, A., & Rickard, J. E. (1992). Aspects of sweetpotato processing in Sichuan Province, People's Republic of China. In G. J. Scott, S. Wiersema, & P. I. Ferguson (Eds.), *Product development for root and tuber crops, vol. 1. Asia* (pp. 217–228). Lima, Peru: International Potato Center (CIP).

Varadharaju, N., Balasubramanian, M., & Parvathy, K. (1992). Studies on the mechanical roasting of sago. *Journal of Food Science and Technology, 29*, 177–178.

Wang, S., Song, B., & Zhang, L. (1995). Status and prospects of sweetpotato processing in China. Paper presented at the SAPPRAD Sweetpotato Processing Study Tour and Workshop, Pingyin, Shandong Province, China. International Potato Center.

Xu, A., & Seib, P. A. (1993). Structure of tapioca pearls compared to starch noodles from mungbeans. *Cereal Chemistry, 70*, 463–470.

Yost, D. A., & Hoseney, R. C. (1986). Annealing and glass transition of starch. *Starch/Staerke, 38*, 289–292.

Zobel, H. F. (1992). Starch granule structure. In R. J. Alexander, & H. F. Zobel (Eds.), *Developments in carbohydrate chemistry*. R. J. Alexander & H. F. Zobel (eds.) St. Paul, MN: American Association of Cereal Chemists.