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Effects of hydrothermal treatment on the physicochemical properties of pregelatinized rice flour

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Abstract

Effects of hydrothermal treatment on the pasting, thermal and hydration properties of rice flour prepared from three *Indica* varieties of milled rice [Taichung Sen Glutinous (TCSW) 1, Taichung Sen (TCS) 10, and TCS 17], which contained 1.2, 17.9 and 28.8% amylose, were studied. Three hydrothermally-treated factors, soaking time, steaming temperature and steaming time were investigated. From the statistical results of an experimental design of L_{27} orthogonal array, the soaking time is a significant factor that affects the pasting properties of three varieties of rice with various degrees of influence. However, the increase of pasting temperature, reduction of peak viscosity and elevation of final viscosity were investigated for all treated non-waxy rice and resulted in the reduction of its breakdown and total setback. The differences of pasting and hydration properties of treated rice flour were attributed to the changes of rigidity of starch granules under treatment. The results of DSC showed that the degree of gelatinization was higher in waxy rice than in non-waxy rice when subjected to the same hydrothermal conditions.

Keywords: Hydrothermal treatment; Pregelatinized rice flour; RVA; DSC; Hydration properties

1. Introduction

Pregelatinized rice flour has been widely used for many foods as a major ingredient, bulking agent or thickening agent. Many popular oriental foods, such as delicate Chinese rice cakes, baby foods and instant rice milk, are also made from pregelatinized rice flour. Traditionally, grinding the roasted or puffed rice kernel from raw rice or parboiled rice is the way to produce pregelatinized rice flour. It has been realized that the physicochemical and functional properties, which are different mainly due to the rice varieties and processing methods, significantly affect the applications of pregelatinized rice flours (Damir, 1985; Hsieh & Luh, 1991; Luh, 1991; Lu, Chen & Lii, 1994).

Since starch is the major component of the rice kernel, the changes of its physicochemical properties during hydrothermal treatment will dominate the properties of pregelatinized rice flour. The hydrothermal treatment of rice for the production of pregelatinized rice flour is a complex process as shown by the changes of physicochemical properties of starch. The rice starch may be physically modified without visible changes in granule appearance when steamed under limited moisture or low temperature conditions (Collado & Corke, 1999; Stute, 1992). The rice starch may be gelatinized with accompanying granule swelling, loss of birefringence and crystallinity, and disruption of starch granule structure when steamed at sufficient moisture and elevated temperature conditions (Atwell, Hood, Lineback, Varriano Marston & Zobel, 1988; Zobel, 1984). While drying steamed rice, the starch may reorient or interact intra- and inter-molecularly due to the loss of water (Mahanta & Bhattacharya, 1989; Ong & Blanshard, 1995; Seow & Teo, 1993). The microstructure of starch molecules will also be affected during further processes, such as roasting, popping or puffing which are applied to raw or hydrothermally-treated rice for the production of pregelatinizated rice flour. All changes of starch granules and starch molecules are associated with the unique physicochemical properties of pregelatinized rice flour and its utilization. Besides the processing methods, the

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effects of rice variety on pasting and thermal properties of parboiled rice or hydrothermally-treated rice starch have also been reported (Biliaderis, Tonogai, Perez & Juliano, 1993; Biswas & Juliano, 1988; Villareal, Juliano, & Hizukuri, 1993). The general effects reported by previous workers (Abraham, 1993; Donovan, Lorenz & Kulp, 1983; Hoover & Vasanthan, 1994; Knutson, 1990; Kulp & Lorenz, 1981; Lorenz & Kulp, 1981; Stute, 1992) include the increase of gelatinization temperature and the change in gelatinization range, X-ray diffraction patterns, swelling volume and solubility of starches, with consequent changes in its functionality. Hoover and Manuel (1996a) investigated the nature and extent of interactions of maize starches during heat-moisture treatment and found that the starch chain interactions occurred within both the amorphous and crystalline regions of the granule. They also reported that the extent of starch reassociations were greater in the amorphous region due to the interactions of amylose-amylose, amylose-lipid, and amylose-amylopectin. Although the crystalline order altered during heat-moisture treatment, the interactions between amylopectin chains in crystalline regions occur only to a limited extent (Hoover & Manuel, 1996a, 1996b).

For rapid evaluation of cooking and processing properties of cereal flours, starches and their products, the Rapid Visco-Analyzer (RVA) is a useful tool because the measurement can be accomplished during a short testing time and only a small amount of sample is required (Jacobs, Erlingen, Clauwaert & Delcour, 1995; Whalen, 1999). The viscographs of starch or cereal flour slurry, from the measurement of the changes in viscosity over a time–temperature profile, can reflect the molecular weight and conformation of starches, which are affected by cereal sources, processing conditions and formulations.

Rice variety and processing parameters play a critical role in achieving the desired functionality and consumer acceptability of products made from pregelatinized rice flour. Although many properties of hydrothermally-treated starches have been studied, relatively little work has been reported on the effects of rice variety and parameters of hydrothermal treatment on the pasting, thermal, and hydration properties of pregelatinized rice flour. In this study, an L_{27} orthogonal array of the Taguchi method (Montgomery, 1991) was used to evaluate the effects of hydrothermal processing conditions on the pasting properties of pregelatinized rice flours, which were prepared from three *Indica* varieties of rice with various contents of amylose. The thermal properties and hydration properties of hydrothermally-treated rice flour were also investigated. It is hoped that the results may give a deeper insight into the changes in pasting, thermal, and hydration properties of pregelatinized rice flour related to various amylose contents and different processing conditions.

2. Materials and methods

2.1. Materials

Three *Indica* varieties of milled rice, Taichung Sen Glutinous 1 (TCSW 1), Taichung Sen 10 (TCS 10), and Taichung Sen 17 (TCS 17), were used for this study. The proximate composition of rice was analyzed according to AACC methods of 44–15, 46–12, 08–01 and 30–20A, for the determinations of moisture, crude protein, ash and crude fat (AACC, 1995). The apparent amylose content of rice was determined by the method of Juliano et al. (1981).

2.2. Hydrothermal treatment

Rice was treated hydrothermally, as shown in Table 1, to investigate the effects of soaking time (i.e. moisture content), steaming temperature and steaming time on the pasting properties of treated rice. After the rice was steamed, it was immediately dried in a 70% relative humidity (RH) cabinet at 45°C for 14–16 h until the moisture content of steamed rice was less of 13±1%. The dried, treated rice was then stored in a 15°C cabinet and ground by a Udy Cyclone Mill with 0.5-mm screen (Udy Corp., Co., USA) for the measurement of physicochemical properties.

2.3. RVA measurements

Pasting properties of hydrothermally-treated rice flour were determined by using a Rapid Visco Analyzer model 3-D (Newport Scientific Pty Ltd., Warriewood, Australia) and Approved Method 61-02 (AACC, 1995). A 13.8% (w/w) rice flour suspension was prepared by placing 4 g (dry basis) rice flour in an aluminium canister which contained 25 g of distilled water. A programmed heating and cooling cycle was used at constant shear rate, where the sample was equilibrated at 35°C for 2 min, heated to 95°C at a rate of 11.8°C/min, held at 95°C for 2.5 min and cooled to 35°C at the same rate. These tests were done in duplicate. A plot of paste viscosity in arbitrary RVA units (RVU) versus time was used to determine the cold (initial) viscosity, peak viscosity (PV), temperature at PV (P_{temp}), final viscosity (FV), breakdown viscosity (BKD = PV–trough), and total setback viscosity (TSB = FV–trough). The first point, at which the viscosity increased at the rate of 1 RVU/s or faster, was determined as the onset temperature of gelatinization (Tg) of rice flour.

The effects of soaking time, steaming temperature and steaming time on the pasting properties of hydrothermally-treated rice were estimated by the mean and signal-to-noise ratios, the larger the better (SN_L) at every level, based on a L_{27} orthogonal array of the Taguchi method (Montgomery, 1991). The mean and SN_L were calculated using Eqs. (1) and (2), respectively.

Table 1
The factors and levels for the L_{27} orthogonal array design

Level	1	2	3
Factor[a]			
A: Soaking	Rinsed and equilibrated (R&E)	Soaked for 1 h at 4°C (S1)	Soaking for 4 h at 4°C (S4)
B: Steaming temperature	75°C	85°C	95°C
C: Steaming time	20 min	40 min	60 min

[a] Factor A was assigned to column 1, Factor B was assigned to column 2, and Factor C was assigned to column 5 of a L_{27} orthogonal array design.

$$\text{Mean} = \left(\frac{1}{n}\sum_{i=1}^{n} yi\right) \quad (1)$$

$$SN_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{yi^2}\right) \quad (2)$$

where SN_L is the signal-to-noise ratio of larger the better, n is the total testing number at the same testing level and y is the corresponding yield of each test. For each factor and level, the most significant effects are those which give the largest SN_L values.

2.4. DSC measurements

Thermal characteristics of hydrothermally-treated rice were studied by using a Differential Scanning Calorimetry (DSC) (MDSC 2910, *TA* Instruments, USA) calibrated with indium before analysis and using an empty pan as reference. A rice sample of 5–5.5 mg (dry basis) was loaded into an aluminium sample pan. Water was added with a microsyringe to the sample pan to give a water content of 70% (w/w). The sample pan was sealed, reweighed and allowed to stand 1 h at room temperature. The sample was then heated from 30 to 140°C at a rate of 5°C/min. From the DSC curve, the onset temperature (T_o), peak temperature (T_p), and transition enthalpy (ΔH) were evaluated using the TA Instruments analysis software program. The degree of gelatinization of hydrothermally-treated rice was also calculated by the following equation (Marshall, Wadsworth, Verma & Velupillai, 1993).

$$SG\,(\%) = \left(1 - \Delta H_{pg}\Delta H_{raw}\right) \times 100 \quad (3)$$

where SG is the gelatinization degree of hydrothermally-treated rice and ΔH_{pg} is transition enthalpy of hydrothermally-treated rice and ΔH_{raw} is transition enthalpy of raw rice.

2.5. Hydration properties

The water absorption index (WAI), water solubility (WS) and swelling power (SP) of hydrothermally-treated rice were measured according to the methods of Chang, Change and Yang (1996) with some modifications. Raw or hydrothermally-treated rice (2.5 g) were weighed and 30 ml of distilled water was added. It was agitated at 30°C for 30 min and then centrifuged at 5000×g for 15 min. The supernatant was dried at 105°C. The WAI was calculated as the ratio of gel weight to dry sample weight. The WS (%) was measured as the dry weight of supernatant divided by the dry weight of sample times 100. The SP was defined as the ratio of the gel weight to the dry sample weight×(1−WS/100).

3. Results and discussion

The proximate compositions of rices are shown in Table 2. The moisture contents of rinsed rice were 22.2±0.5% for all three rice varieties. The soaked rice was saturated after 30 min soaking, and there were no significant differences in the moisture contents within the same variety, which were soaked either for 1 or 4 h. The moisture contents were 34.8, 31.5, and 29.8% for TCSW 1, TCS 10, and TCS 17, respectively.

Generally, the physical modification of starches, through hydrothermal treatment, includes annealing and heat−moisture treatment, depending on the temperature and moisture applied to the starches (Collado & Corke, 1999). Annealing is a physical modification of starch in excess water at temperatures below gelatinization, while heat-moisture treatment of starch is a modification resulting from the exposure of it to higher temperature at very restricted moisture contents (<30%). The hydrothermal treatments of rice, applied for this study, include heat−moisture treatment on the raw rice

Table 2
Proximate composition of rice

Variety	Moisture (%)	Protein	Ash	Fat	Amylose
		(%, dry basis)			
TCSW 1	11.96	7.85	0.49	0.72	1.20
TCS 10	12.20	7.83	0.73	0.37	17.9
TCS 17	12.20	8.26	0.46	0.69	28.8

(moisture content: 22.2–34.8%) following the annealing treatment on the steamed rice (moisture content: 54.3–65%), dried at 45°C under 70% RH for 14–16 h.

3.1. Pasting properties

The pasting curve obtained from RVA is a measure of the viscosity of starch or cereal suspension during the heating cycle, which reflects the molecular events occuring in starch granules. Therefore, the integrity of starch granule and hydration properties resulting from the starch native properties, or from the inter- or intra-molecular interactions during hydrothermal treatment, can be easily investigated by measuring the pasting curves of cereal flour before and after modification.

3.1.1. TCSW 1 rice

The typical RVA viscographs of hydrothermally-treated TCSW 1 rice are shown in Fig. 1 and only the results of rinsed and equilibrated (R&E) rice and the rice soaked for 1 h (S1) before steaming at 95°C are shown here. The length of soaking time, i.e. soaked for 1 or 4 h did not significantly affect the patterns of viscographs of hydrothermally-treated rice. When the rice was steamed under limited water (22.2%), i.e. rinsed and equilibrated before steaming, the pasting properties of treated rice were not significantly affected (Fig. 1a). But it was found that the PV decreased and the trough and FV increased in all cases of treated rice. Therefore, the BK) and total TSB were decreased. Stute (1992) also reported similar findings in the changes of pasting properties of heat-moisture-treated potato starch. These changes of pasting characteristics indicated that starch molecules have some degree of reassociation during steaming and drying period. Under the limited moisture conditions (R&E), the gelatinization of rice starch was restricted no matter what steaming temperature or steaming time was used on the TCSW 1. This is shown by the fact that there are no changes in ΔH values of DSC measurements of raw and treated rice (data not shown).

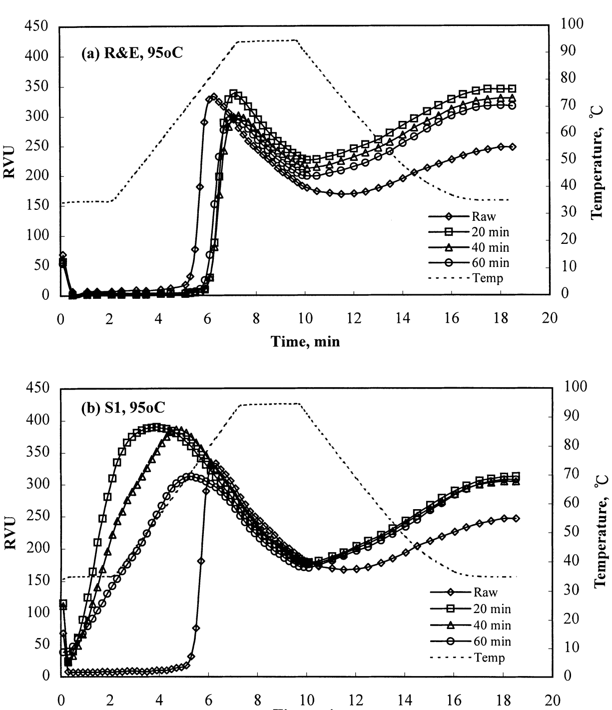

Fig. 1. Viscograph of hydrothermally-treated TCSW 1 [13.8% (w/w)] rice prepared under different soaking and steaming conditions. Raw rice was also analyzed for comparison. R&E indicates that the rice was rinsed and equilibrated at 4°C overnight and S1 indicates that the rice was soaked for 1 h before steaming.

In contrast to the viscographs of rinsed and equilibrated (R&E) rice (Fig. 1a), the pasting properties of treated TCSW 1 rice (S1 or S4), which was soaked before steaming, were significantly affected by the steaming temperature and steaming time (Fig. 1b). When rice was steamed under high moisture content (34.8%), the steaming temperature had a critical effect on the pasting characteristics of pregelatinized rice flour. It was found that the cold viscosity of treated rice flour was significantly increased when steamed at 85 and 95°C, while the temperature at peak (P_{temp}), and PV was decreased with increase in steaming time. The high cold viscosity of treated TCSW 1 showed the typical hydration property of pregelatinized waxy rice flour. The disruption of molecular order within starch granules during steaming caused loss of starch granule integrity and the destruction of crystallinity, which resulted in its cold soluble properties by creating high viscosity at low temperature. Therefore, the moisture content, while steaming, and steaming temperature are the critical processing conditions for hydrothermally-treated TCSW 1 rice. The minimum moisture content and temperature during steaming required for marked changes in pasting properties were 34.8% (dry basis) and 85°C, respectively.

Effects of the three hydrothermal factors, soaking time, steaming temperature and steaming time, on the pasting properties of treated TCSW 1 were evaluated by the values of mean and SN_L, which were calculated from the results of an L_{27} orthogonal array (Table 3). When the levels with the largest SN_L of every factor are chosen as processing parameters, the maximum effect on the specific pasting characteristic can be expected (Taguchi, 1986). The results showed that the peak viscosity of treated TCSW 1 rice flour was significantly increased when TCSW 1 rice was soaked for 1 h and then steamed at 95°C for 20 min. The temperature at the peak was the lowest when the TCSW 1 rice was hydrothermally-treated under the above conditions. The FV of hydrothremally-treated TCSW 1 was increased with increase in steaming temperature, but decreased with increase in steaming time and moisture content while steaming. The BKD and TSB of hydrothermally-treated TCSW 1 were also

Table 3
Effect of three factors on the pasting properties of hydrothermally-treated TCSW 1

Pasting properties	Raw	Steaming temperature (°C)			Steaming time (min)			Soaking time		
		75	85	95	20	40	60	R&E	1 h	4 h
Peak viscosity (PV, RVU)	333	313 (49.90)[a]	310 (49.66)	346 (50.60)	348 (50.76)	324 (50.05)	297 (49.40)	311 (49.80)	320 (50.47)	320 (49.86)
Temperature at peak (P_{temp}, °C)	83	90 (39.11)	84 (38.21)	73 (36.66)	77 (37.04)	84 (38.22)	86 (38.52)	92 (39.25)	77 (37.23)	78 (37.43)
Final viscosity (FV, RVU)	247	295 (49.35)	309 (49.75)	312 (49.85)	311 (49.83)	306 (49.66)	298 (49.46)	321 (50.11)	303 (49.62)	291 (49.25)
Breakdown (BKD, RVU)	171	131 (42.27)	124 (40.82)	161 (42.65)	160 (43.34)	137 (41.53)	119 (40.97)	106 (40.02)	159 (43.50)	151 (42.82)
Total setback (TSB, RVU)	85	182 (45.17)	194 (45.73)	207 (46.28)	191 (45.57)	197 (45.83)	195 (45.72)	190 (45.48)	195 (45.74)	198 (45.90)

[a] SN_L of each factor at every level is indicated in parentheses.

significantly affected by the steaming time and steaming temperature. The largest BKD and TSB of hydrothermally-treated TCSW 1 rice could be obtained by steaming at 95°C for 20 min.

3.1.2. TCS 10 rice

The RVA viscographs of hydrothermally-treated TCS 10 rice (R&E and S1 steamed at 95°C) are shown in Fig. 2. The main effects of three hydrothermal factors expressed as the values of mean and SN_L, are summarized in Table 4. In general, decrease of PV, and increase of trough and FV, which have been found in the treated TCSW 1 (Fig. 1a), were also observed in all of the hydrothermally-treated TCS 10. Therefore, the decrease in BKD and increase in TSB were observed in the hydrothermally-treated TCS 10 rice flour. In contrast to the results of hydrothermally-treated TCSW 1, which were steamed at elevated temperature (85 and 95°C) under high moisture content (S1 and S4), no significant cold viscosities were observed. The PV of treated TCS 10 rice flour was significantly decreased and P_{temp} delayed compared to the results of raw TCS 10 rice (Fig. 2b). As shown in Table 4, the highest gelatinization temperature, the lowest peak viscosity, and the smallest BKD could be obtained from the viscographs of treated TCS 10 rice flour that was steamed at 95°C for 1 h after soaking for 1 h. These results indicate that the granule rigidity and molecular reassociation are significantly enhanced by the hydrothermal treatment applied in this study, while the degree of change in the pasting properties depends on the combination effects of moisture, temperature and time on the starch granules during soaking, steaming and drying period.

3.1.3. TCS 17 rice

The RVA viscographs of hydrothermally-treated TCS 17 rice (R&E and S1 steamed at 95°C) are shown in Fig. 3. The pasting properties were significantly affected by the degree of treatment. As shown in Fig. 3, the change in viscosity of treated TCS 17 rice is a combination effect of moisture content during steaming and drying, steaming temperature and steaming time. Similar to the pasting curves of treated TCSW 1 (Fig. 1a) and TCS 10 (Fig. 2), the viscographs of treated TCS 17 showed a marked increase of Tg and decrease of viscosity under the RVA cooking process. It was found that the viscosity of hydrothermally-treated TCS 17 rice decreased

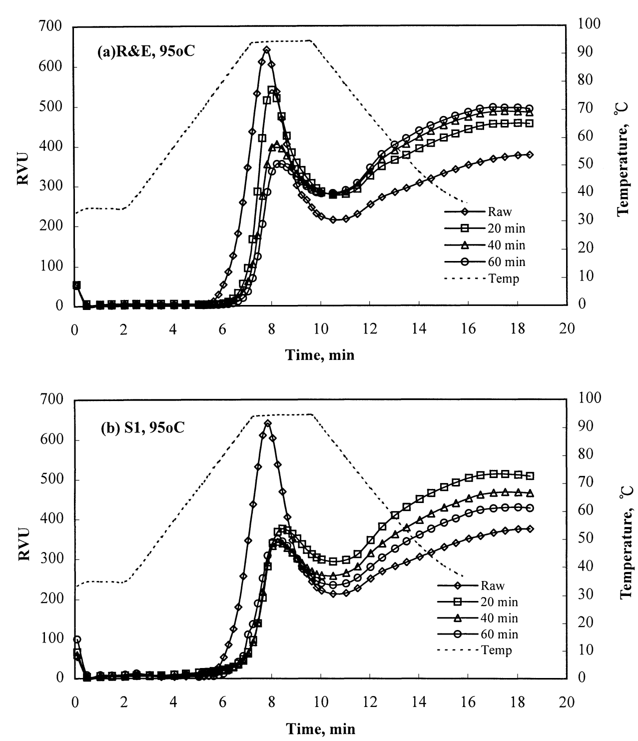

Fig. 2. Viscograph of hydrothermally-treated TCS 10 [13.8% (w/w)] rice prepared under different soaking and steaming conditions. Raw rice was also analyzed for comparison. R&E indicates that the rice was rinsed and equilibrated at 4°C overnight and S1 indicates that the rice was soaked for 1 h before steaming.

Table 4
Effect of three factors on the pasting properties of hydrothermally-treated TCS 10

Pasting property	Raw	Steaming temperature (°C)			Steaming time (min)			Soaking time		
		75	85	95	20	40	60	R&E	1 h	4 h
Gelatinizazation temperature (Tg, °C)	75	78 (37.83)[a]	82 (38.25)	84 (38.46)	81 (38.17)	81 (38.13)	82 (38.22)	82 (38.26)	81 (38.17)	81 (38.15)
Peak viscosity (PV, RVU)	641	514 (53.94)	452 (52.84)	388 (51.57)	498 (53.55)	444 (52.60)	412 (52.01)	518 (53.88)	417 (52.19)	419 (52.17)
Final viscosity (FV, RVU)	376	415 (52.33)	461 (53.24)	479 (53.58)	460 (53.22)	451 (53.00)	444 (52.84)	460 (53.20)	450 (52.96)	446 (52.90)
Breakdown (BKD, RVU)	429	281 (48.29)	185 (44.57)	116 (39.76)	229 (44.01)	190 (43.17)	162 (41.71)	248 (44.43)	162 (42.18)	171 (42.30)
Total setback (TSB, RVU)	164	112 (40.95)	122 (41.71)	127 (42.03)	123 (41.70)	118 (41.43)	120 (41.50)	116 (41.27)	123 (41.75)	122 (41.62)

[a] SN_L of each factor at every level is indicated in parentheses.

after treatment and the magnitude of decrease significantly increased with increase in the degree of treatment. With the exception of high cold viscosity, the pasting properties of TCS 17 rice are similar to a Type C pasting profile, which is characterized by the lack of pasting peak viscosity and no breakdown, as defined by Schoch and Maywald (1968). Collado and Corke (1999) also reported this in their study of two heat–moisture-treated varieties of sweet potato starches, which contained 15.2 and 28.5% amylose, respectively.

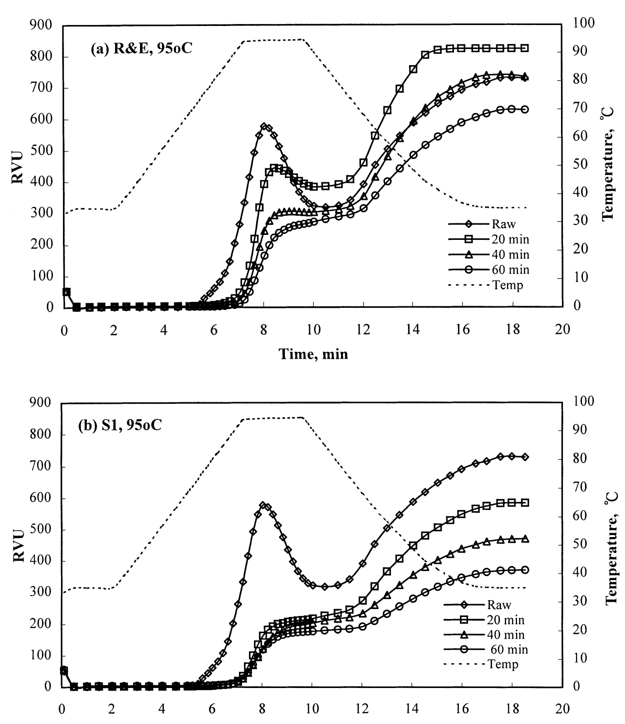

Fig. 3. Viscograph of hydrothermally-treated TCS 17 [13.8% (w/w)] rice prepared under different soaking and steaming conditions. Raw rice was also analyzed for comparison. R&E indicates that the rice was rinsed and equilibrated at 4°C overnight and S1 indicates that the rice was soaked for 1 h before steaming.

Table 5 is the summary of main effects of three hydrothermal factors on the pasting properties of treated TCS 17 rice flour. The Tg and TSB of all treated TCS 17 rice flours are higher than that of raw rice flour, while the PV, FV and BKD are smaller than that of raw rice flour. The differences between treated rice and raw rice flour increased as steaming temperature and time or soaking time increased. When TCS 17 rice was soaked for 1 or 4 h and then steamed at 95°C for 60 min, the highest Tg and the lowest PV, FV, BKD and TSB could be obtained.

As is obvious from the viscographs and their calculated mean and SN_L values, the starch granules and/or starch molecules of three varieties of rice respond differently under the same conditions of hydrothermal treatment. Therefore, the changes in the pattern of viscograph and magnitude of viscosity of treated rice flour are dependent on the rice variety. According to the changes in viscographs of three varieties of rice treated under low moisture content (R&E) or low steaming temperature (75°C), it can be proposed that the amorphous regions of the starch granule are the first feasible portion to be modified (Figs. 1, 2 and 3a). Then, amylose molecules are the second feasible portions to suffer from the hydrothermal effect; the degrees of reassociation of amylose molecules are proportional to the degree of treatment. This can be demonstrated from the gradual decrease in PK and increase of FV of treated TCS 17 when the degree of treatment was gradually increased (Fig. 3). Under conditions of high moisture (such as S1 or S4) and elevated steaming temperature (85 or 95°C), gelatinization of starch can take place. The patterns of viscographs of gelatinized rice flours are totally different due to various amount of amylose in the rice flour. The viscograph of treated TCSW 1 indicated that the swollen gelatinized starch granules are more open and susceptible

Table 5
Effect of three factors on the pasting properties of hydrothermally-treated TCS 17

Pasting property	Raw	Steaming temperature (°C)			Steaming time (min)			Soaking time		
		75	85	95	20	40	60	R&E	1 h	4 h
Gelatinizazation temperature (Tg, °C)	72	84 (38.43)[a]	89 (38.97)	90 (39.10)	86 (38.70)	88 (38.88)	89 (38.94)	85 (38.54)	89 (38.97)	90 (39.03)
Peak viscosity (PV, RVU)	579	401 (51.30)	274 (48.00)	228 (45.77)	341 (49.12)	293 (47.71)	269 (46.87)	409 (51.40)	252 (47.25)	242 (46.26)
Final viscosity (FV, RVU)	736	787 (57.89)	678 (56.09)	525 (53.03)	727 (56.79)	656 (55.19)	606 (54.04)	789 (57.84)	632 (55.21)	568 (53.56)
Breakdown (BKD, RVU)	418	70 (21.24)	10 (1.09)	8 (1.02)	39 (3.52)	30 (3.40)	17 (1.71)	63 (6.29)	10 (1.76)	13 (1.72)
Total setback (TSB, RVU)	157	456 (53.15)	413 (51.77)	304 (47.96)	426 (52.27)	393 (50.57)	354 (48.93)	444 (52.84)	390 (50.72)	339 (48.59)

[a] SN_L of each factor at every level is indicated in parentheses.

to hydration so that they can cause a high cold paste viscosity. The viscograph of treated TCS 10 and TCS 17 were totally different from the viscographs of treated TCSW 1. Under the same conditions, the leached amylose molecules of TCS 10 and TCS 17 retrograded quickly after gelatinization and during drying. The strong reassociation of amylose molecules of gelatinized rice caused the low PV and high FV of viscographs of treated TCS 10 and TCS 17 rice. The effects were more significant in treated TCS 17 than in treated TCS 10 due to the high amylose content of TCS 17.

3.2. Thermal properties

The thermal properties of hydrothermally-treated rice were investigated by the measurements of DSC and the results of three varieties of rice, which were soaked for 1 h and then steamed at 95°C for 20, 40, and 60 min, respectively, are shown in Table 6. The DSC results of raw TCSW 1, TCS 10 and TCS 17 are also included in this table for comparison. An increase in gelatinization temperature (T_{1o}) was observed for all of the treated rice except the fully gelatinized TCSW 1 (S1 or S4, steamed at 95°C for 60 min) for which no peaks could be detected below 100°C. But deviations of gelatinization temperature were found between the measurements of RVA and DSC. Three phase-transition zones were observed in the samples of raw rice, and most of the treated rice showed the starch polymorphism. Ong and Blanshard (1995) also reported that at least three states of starch, which are ungelatinized, recrystallized and amylose-lipid complex, could be observed in the parboiled rice. According to the gelatinization degree of treated rice, calculated by taking the ratio of enthalpy of gelatinization peak (ΔH_1) of the treated rice to the ΔH_1 of raw rice, the ΔH_1 of rice treated under low moisture (R&E) was not significantly different ($P<0.05$) from the raw rice, indicating that no gelatinization occurred in those treated samples (data not shown). Similar results are also found in legume starch and maize starches that were physically modified by undergoing heat-moisture treatments (Hoover & Manuel, 1996a, 1996b). As shown in Table 6, the degree of starch gelatinization (SG,%) depended on the rice varieties and conditions of hydrothermal treatment. However, a lower degree of gelatinization was found in non-waxy rice than in waxy rice when treated under the same conditions. This may be due to (1) the native properties of rice, and (2) the acceleration of molecular rearrangement of non-waxy rice during hydrothermal treatment. The reassociation may occur mainly on the amylose in the amorphous regions, which will result in recrystallization, perfection of the small crystalline regions or strong interactions of amylopectin and/or amylose. The observations of multiple endothermal peaks and delay of gelatinization temperature of hydrothermally-treated rice could be further evidence of the phenomena of starch molecule reassociation. However, the mode and magnitude of reassociation of starch molecules are hardly predicted by the present DSC results.

3.3. Hydration properties

WAI, WS and SP of raw rice as well as the treated rice (S1, steamed at 95°C) are shown in Table 7. The hydration properties of treated rice were different among three rice varieties but not significantly affected by the steaming time as shown in Table 7. The WAI and SP were similar among three varieties of raw rice, but the water solubilities were TCSW 1 (9.84%) > TCS 10 (6.09%) > TCS 17 (3.15%). After hydrothermal treatment, the WAI and SP of treated TCSW 1 rice significantly increased (ca. 3 times that of raw rice), while those of treated TCS 10 and TCS 17 increased slightly (ca. 1.2–1.8 times of raw rice). The WS of treated TCSW 1, TCS 10 and TCS 17 were about 150, 93 and 63%,

Table 6
DSC thermal properties of raw and hydrothermally-treated rice of TCSW 1, TCS 10 and TCS 17 prepared by soaking for 1 h and then steaming at 75, 85 or 95°C for 1 h

Steaming condition	First peak			Second peak			SG (%)[a]
	T_{1o} (°C)	T_{1p} (bk7C)	ΔH_1 (J/g, db)	T_{2o} (°C)	T_{2p} (°C)	ΔH_2 (J/g, db)	
TCSW 1 (raw)	64.1	71.8	12.6	88.9	95.1	0.7	
S1, 75/60	70.8	77.8	2.9	105.9	110.6	0.5	77.0
S1, 85/60	77.4	83.0	0.6	105.8	112.3	0.8	95.2
S1, 95/60	–	–	–	102.4	111.5	1.5	100.0
TCS 10 (raw)	66.2	71.9	9.6	89.7	98.2	1.5	
S1, 75/60	66.6	75.2	2.2	89.1	98.0	2.5	77.1
S1, 85/60	68.4	77.5	0.5	94.9	98.7	0.7	94.8
S1, 95/60	78.2	84.9	0.2	94.2	98.5	0.7	97.9
TCS 17 (raw)	63.2	68.9	8.3	87.5	96.2	1.0	
S1, 75/60	70.1	75.3	3.1	91.3	95.8	0.5	62.7
S1, 85/60	70.0	75.3	1.1	98.7	100.9	0.6	86.8
S1, 95/60	75.8	80.7	0.6	94.5	99.1	0.8	92.8

[a] SG, degree of gelatinization of hydrothermally-treated rice.

Table 7
Effect of different steaming times on the water absorption index, water solubility, and swelling power of hydrothermally-treated rice

Rice variety	Heat–moisture treatment	Water absorption index (WAI)	Water solubility (WS,%)	Swelling power (SP)
TCSW 1	Raw	2.38	9.84	2.42
	S1,[a] 95°C/20 min	6.86	11.55	7.13
	S1, 95°C/40 min	7.05	15.09	7.42
	S1, 95°C/60 min	6.68	15.57	7.05
TCS 10	Raw	2.66	5.59	2.21
	S1, 95°C/20 min	3.22	5.90	3.26
	S1, 95°C/40 min	3.27	6.05	3.30
	S1, 95°C/60 min	3.09	5.68	3.12
TCS 17	Raw	2.87	3.15	2.15
	S1, 95°C/20 min	3.72	2.04	3.74
	S1, 95°C/40 min	3.89	2.13	3.91
	S1, 95°C/60 min	3.88	1.98	3.90

[a] S1, 95°C/20 min, /40 min or /60 min: dried pregelatinized rice was prepared by being soaked for 1 h, then steamed at 95°C for 20, 40 or 60 min and dried in a 70% RH cabinet at 45°C for 14–16 h.

respectively, compared with the raw rice. These results indicate that starch granules of pregelatinied TCSW 1 are more susceptible to water hydration; therefore, the WAI and SP increase significantly after treatment. The increase of WS of treated TCSW 1 is attributed to increased numbers of small fragments of amylopectin or amylose leaching out through opened starch granules, whose structures are changed during hydrothermal treatment. In contrast to the treated TCSW 1, the decrease of WS of treated TCS 10 and TCS 17 is attributed to the enhancement of reassociation of amylose and amylopectin, which results in increasing the rigidity of pregelatinized rice. Therefore, the reassociation of amylose is one major contributor to the changes of hydration properties of treated non-waxy rice. The higher the amount of amylose in rice, the more rigid will be the structure of its hydrothermally-treated rice. Less WAI, WS and SP of hydrothermally-treated rice will be observed for the variety with higher amylose content.

4. Conclusions

Pasting and hydration properties of hydrothermally-treated rice are markedly dependent on the rice variety (or amylose content). The opposite effects on the treated waxy and non-waxy rice may be due to the amorphous regions and semi-crystalline structure of starch granules, resulting from the different compositions of amylose and amylopectin. Under limited moisture content (R&E) the rice was undergoing physical modification resulting in the delay of T_g, reduction in PV, and slight increase of FV. While the rice was treated under high moisture conditions (S1 or S4) or elevated temperature (85 or 95°C) for extended time, the degree of gelatinization (SG) of starch was greatest for TCSW 1 and smallest for TCS 17, as measured by using DSC. Pasting properties of pregelatinized rice flour, measured by using RVA, indicate that the integrity of TCSW 1 starch granules become less while the TCS 17 starch granule is more rigid after hydrothermal treatment. The modifications of starch granules or the degrees of reassociation of starch molecules of rice are reflected by the changes of their hydration properties before and after hydrothermal treatment.

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