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Effects of hydrothermal treatments on the rheological properties of potato starch

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Abstract

Potato starch was hydrothermally treated at moisture levels ranging from 20 to 40% and at temperatures 3% below the gelatinization peak temperatures (in K). The treatments had a great impact on the rheological behavior as studied with a rapid visco analyzer (RVA) and dynamic viscoelastic measurements. The extent of the observed effects did not only depend on the specific treatment but also on the starch concentrations investigated (3.0, 6.6, and 20.0%). For the dynamic measurements, the gel storage moduli were related to swelling power and close packing concentration. The increase in onset temperature of viscosity development and the decrease in peak viscosity observed with RVA as a consequence of hydrothermal treatments, were also attributed to the decreases in swelling power and solubility.

Keywords: Starch; Rheology; Hydrothermal treatment

1. Introduction

Hydrothermal treatments of starch granules involve their storage at a certain moisture level during a certain period of time at a temperature below the gelatinization temperature (but above the glass transition temperature). When keeping in 'excess' water this process is called 'annealing' [1–7], while the term 'heat-moisture treatment' is used when low moisture contents are applied [8–14].

As has been demonstrated before, hydrothermal treatments change the physico–chemical properties of starch. An increase in the gelatinization temperature and changes in the gelatinization temperature range and enthalpy values have been observed after hydrothermal treatments [2,3,6,9,13,14]. In some cases heat-moisture treatment of potato starch leads to transformation from the B- to the A-type crystalline structure [5,8,14]. Only very little is known about the impact of hydrothermal treatments on the rheological properties of starch. Stute [5] investigated the impact of hydrothermal treatments on the Brabender pasting properties. A higher viscosity development onset temperature and a lower peak viscosity was observed after treatment (at 20% moisture and 110 °C or 120 °C, or at 83% moisture and 52 °C) while end viscosity values were lower after intense treatments or higher after moderate treatments. Hoover and Vasan-

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than [15] carried out a study on the flow properties of hydrothermally treated starches. With a cone and plate viscometer they found significant effects on the flow properties (shear thinning index and consistency index) of gelatinized starch suspensions (6%).

Studies on native starch have shown that different factors such as granule rigidity and extent of granule swelling [16–20], size distribution of the granules [21], degree of amylose leaching [19,20,22,23], starch processing conditions (e.g. pasting temperature, shearing, heating rate, etc.) [19,21,24] all have an influence on the rheological properties of starch suspensions and gels. Taylor and Bagley [25,26] proposed a model describing the rheology of suspensions of swellable particles. It was refined and successfully applied to chemically modified and native starches [25–29].

The purpose of our work was to investigate both by viscometry and small strain dynamic rheology the impact of a series of hydrothermal treatments on the rheological properties of potato starch. To that end, starch granules were stored at a temperature 3% below the gelatinization peak temperature at the specific moisture content. So far, most treatments have been carried out at specific temperature-moisture conditions without taking into account the gelatinization temperature of the starch at the moisture level used during the treatment [5,8,9,11–14]. Therefore, in those experiments partial gelatinization could have occurred during the treatment without knowing it. Furthermore, we wanted to investigate the rheological properties at different starch concentrations and both by RVA viscometry and dynamic rheology. Only small deformations are applied during dynamic rheology measurements, and therefore, the destructive effects on the gel structure are negligible.

2. Experimental

Potato starch (Meridal G) was obtained from Amylum (Aalst, Belgium). Potato amylose was from Sigma Chemical Co. (St. Louis MO, USA, A0512). Moisture content (m.c.) was determined by drying a sample (15 min) with an infrared moisture balance (Cenco, Breda, The Netherlands) and was found to be 15.5%. According to the supplier, the starch contained less than 0.3% ash and less than 0.2% protein.

Differential scanning calorimetry (DSC).—DSC-experiments were performed with a Seiko DSC-120 instrument (Kawasaki Kanagawa, Japan). Indium and tin were used as standards. Approximately 7 mg of starch was accurately weighed in an aluminium sample pan. Starches were analyzed at moisture levels varying from 20 to 67% by weight. To that end, moisture contents were adjusted as explained below. Sample pans were hermetically sealed and heated from 30 to 140 °C at a rate of 5 °C/min with an empty pan as reference. Transition temperatures reported are the gelatinization peak temperatures (T_p). Each sample was analyzed in triplicate.

Hydrothermal treatments.—The moisture content of starch was adjusted by spraying the appropriate amount of water, containing sodium azide, on 25 g of starch to obtain samples with 20, 25, 30, 35, and 40% moisture [by weight i.e. (water × 100)/(water + dry matter)] and 0.013% sodium azide (by weight). After thorough mixing, samples were equilibrated overnight at room temperature in a hermetically sealed container. Final moisture contents were then determined again. The starch of appropriate water content was subsequently stored for 16 h at a constant temperature. The storage temperatures (T_{st}) were chosen as a function of the gelatinization temperatures (determined with differential scanning calorimetry) of the native starch at the specific moisture contents. By analogy with previous experiments [7], the samples were stored at moisture content 'm' and at a temperature (T_{st}) 3% below the gelatinization peak temperature (T_p), determined at the specific moisture content 'm' i.e. $T_{st_m} = 0.97 \times T_{p_m}$ (in K). For potato starch adjusted to e.g. a moisture content of $m = 25\%$, T_{p_m} was 109 °C or 382 K and thus, the storage temperature was 0.97 × 382 K or 97 °C.

Dynamic rheological testing of the starch gels.—Starch gels were prepared by heating starch slurries of 3.0, 6.6, or 20.0% starch (dry matter, in weight) in a hermetically sealed stainless steel container disk as described by Biliaderis and Tonogai [30] with slight modifications. The disk (Fig. 1) with the starch slurry was immersed in a boiling water bath (15 min) and subsequently cooled in a water bath at 25 °C (15 min). Rheological measurements were made 10 min after cooling. With the stainless steel container, gels of 2 mm thickness were obtained. Dynamic oscillation measurements were performed with a Bohlin VOR rheometer (Bohlin Reologi, Lund, Sweden) using parallel plates (30 mm diameter) and a torque element of 12.02 or 1.58 g cm. Gel disks with a diameter of 30 mm were cut out of the obtained gel and placed between the parallel plate geometry. A plexiglass cover was placed over it to prevent moisture loss during the measurement. The dynamic measurements were carried out at 25 °C, with a frequency

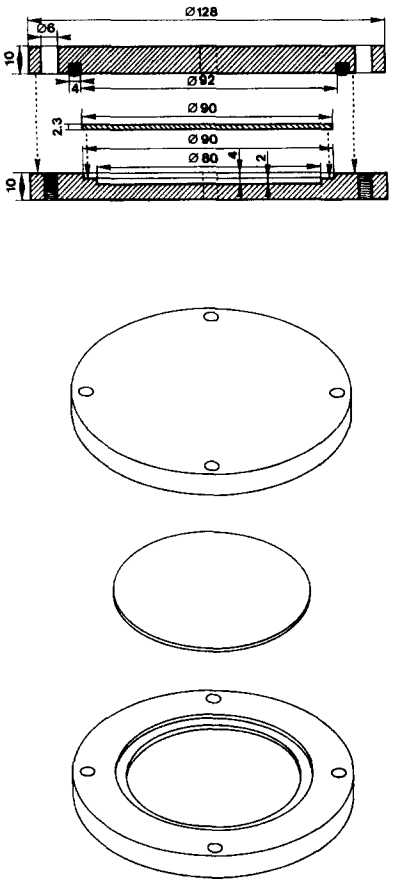

Fig. 1. Stainless steel holder for the preparation of the starch gels of 2 mm thickness for analysis by dynamic rheology.

of 0.2 Hz and below 0.5% strain, i.e. well within the linear viscoelastic range of all gels. To determine the linear viscoelastic range of starch gels, strain sweeps were carried out.

Viscosity measurements.—Viscosity analysis was performed with a Newport Scientific (Sydney, Australia) Rapid Visco Analyzer (RVA). Starch suspensions (3.0 and 6.6% dry matter, total weight of 25.0 g) were subjected to temperature–time profile 1: a heating step from 50 to 95 °C at 6.43 °C/min (after an equilibration time of 2 min at 50 °C), a holding phase at 95 °C for 8 min, a cooling step from 95 to 50 °C at 6.43 °C/min and a holding phase at 50 °C for 17 min. Suspensions of 20.0% starch could not be analyzed since viscosity values were too high during gelatinization. All measurements were performed in duplicate. Starch suspensions (6.6% dry matter, total weight of 25 g) were also subjected to temperature–time profile 2: a heating step from 50 to 95 °C at 6.43 °C/min (after an equilibration time of 2 min at 50 °C), a holding phase at 95 °C for 8 min, a cooling step from 95 to 20 °C at 12.5 °C/min.

Amylose leaching (AML), solubility (S), swelling power (SP), and close packing concentration (C^*).—Starch suspensions (0.25% dry matter) were heated for 15 min in a bath with boiling water and were resuspended every min, or were subjected to the first 17 min of RVA temperature–time profile 1. The starch samples were then centrifuged at 2400 × *g* for 15 min and the supernatant was removed with a pipette. Both the total carbohydrate (phenol–sulfuric acid method [31]) as well as the amylose contents (blue value procedure [32]) of the supernatants were measured. From these results, amylose leaching and solubility were calculated taking into account the fact that the supernatant was only part of the volume of the system (thus, the obtained concentration values were multiplied by the volume of the supernatant instead of by the volume of the total system). The sediments were weighed and swelling capacity (SP, g/g) and close packing concentration (C^*, %) were calculated as follows:

$$\text{SP} = \text{sediment weight}/[\text{starch weight (dry matter)} \times (100\% - \%\ \text{of total carbohydrates in solution})]$$

$$C^* = \frac{\text{starch weight (dry matter)} \times 100\%}{\text{sediment weight}}$$

For the analysis of amylose contents, supernatants (1.0 mL) were pipetted into a 50.0 mL flask. After addition of 0.1 M NaOH (0.5 mL), the samples were boiled for exactly 3 min and immediately cooled in an ice bath. After neutralization with 0.1 M HCl (0.5 mL), 20.0 mL of a potassium hydrogen tartrate solution (5.0 g/L) were added. Deionized water (approximately 43 mL) and 0.5 mL of an iodine solution (200.0 mg I_2 and 2.0 g KI/100 mL) were added and the total volume was adjusted to 50.0 mL with deionized water. After thorough mixing, the solutions were allowed to rest for 20 min at room temperature. The extinction was then measured at 680 nm. Pure potato amylose was used for the calibration curve. Analyses of AML, *S*, SP, and C^* were performed at least in triplicate.

Polarization microscopy.—Photomicrographs were taken at the end of the RVA cycle of 3.0 and 6.6% suspensions using an Olympus BHS laboratory binocular microscope (Tokyo, Japan).

Statistical evaluation.—The statistical analyses were performed using the general linear model [33] including Tukey's studentized range test for pairwise comparisons (5% significance level).

3. Results and discussion

Gelatinization temperature as a function of moisture content.—As has been demonstrated before [34,35], DSC gelatinization characteristics of starch depend on the moisture content. At moisture levels of 67% or more a single endotherm occurs noted as the *G* endotherm [34]. With decreasing moisture content, the intensity of the *G* endotherm decreases while a second endotherm develops at a higher temperature. The latter endotherm is referred to as the *M* endotherm [34]. The *M* endotherm occurs at a higher temperature and is less intense when moisture content is reduced further.

As indicated above, for the hydrothermal treatments starch samples were stored at moisture content '*m*' and at a temperature 3% below T_p, determined at the specific moisture content '*m*' i.e. $T_{st_m} = 0.97 \times T_{p_m}$ (in K). By doing so, gelatinization was avoided and starches were treated in a 'standardized' way. The temperature-moisture conditions applied during hydrothermal treatment of the starch are indicated as (×) in Fig. 2. In Table 1 the exact moisture-temperature conditions applied are given in the first column.

Dynamic rheological properties and amylose leaching (AML), solubility (S), swelling power (SP), and close packing concentration (C^*).—Table 1 shows the impact of the hydrothermal treatments on the storage moduli (G'), the loss moduli (G''), and the loss tangents (tan δ) of 20.0% gels. G' values (elastic responses) for all starch gels were more than one order of magnitude higher then the G'' values (viscous responses). This is a typical observation for a gel system [36]. Hydrothermal treatment increased G' values (elastic responses) although the extent of the effect varied with the treatment (Table 1). However, G'' values (viscous responses) were not significantly different.

The same effects were observed for gels of 6.6% starch (Table 2), although absolute values were lower because of the lower starch concentration. G' was higher for hydrothermally treated starches but the extent of the effect did not follow the same order as for the 20.0% gels. Hydrothermal treatments, except treatment with 40% moisture at 52 °C, led to significant increases in G'' values, but the increase was smaller than that observed for the G' values. Therefore, tan δ decreased as a result of the treatments. Gels of 3.0% starch showed very low values both for G' as well as for G'' (Table 3). In contrast with what was observed for the 20.0 and 6.6% gels, some hydrothermal treatments resulted in lower G' values for the 3.0% gels than for the native starch.

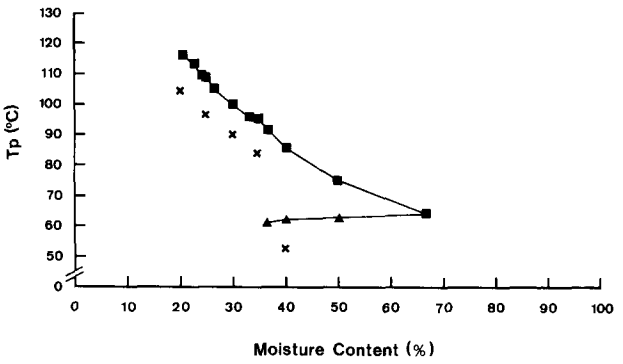

Fig. 2. Gelatinization peak temperatures (▲, T_p of *G* endotherm; ■, T_p of *M* endotherm) of potato starch as a function of moisture content. Symbols (×) indicate temperature-moisture conditions applied during the hydrothermal treatment of starch.

AML, *S*, SP, and C^* readings are listed in Table 4. The levels of AML and *S* were expressed as the percentage of the total starch (dry weight). Since the quantities of leached amylose equalled those of total leached carbohydrates, virtually no amylopectin leached out of the granules. Low values for AML indicated that only a fraction of the amylose had leached out (total amylose content of potato starch is about 22% [37]). Hydrothermal treatment decreased AML, *S*, and SP. This is in agreement with results of Hoover and Vasanthan [14,15], who also found a decrease in the swelling factor and amylose leaching

Table 1
Storage moduli (G'), loss moduli (G''), and loss tangents (tan δ) of 20% gels of native and hydrothermally treated starches

Treatment	G' (Pa)		G'' (Pa)		Tan δ
None	610	A [a]	85	A [a]	0.139
20% m.c., 105 °C	3,920	B	145	A	0.037
25% m.c., 97 °C	12,600	C	88	A	0.007
30% m.c., 90 °C	5,110	B D	135	A	0.026
35% m.c., 84 °C	7,390	D	61	A	0.008
40% m.c., 52 °C	1,370	A	165	A	0.120

[a] Different characters indicate significant differences (within one column) on 5% level according to the Tukey test.

Table 2
Storage moduli (G'), loss moduli (G''), and loss tangents (tan δ) of 6.6% gels of native and hydrothermally treated starches

Treatment	G' (Pa)		G'' (Pa)		Tan δ
None	100	A [a]	18	A [a]	0.180
20% m.c., 105 °C	740	A C	67	B	0.091
25% m.c., 97 °C	1,650	B C	49	B	0.030
30% m.c., 90 °C	1,190	C	55	B	0.046
35% m.c., 84 °C	2,410	B	49	B	0.020
40% m.c., 52 °C	210	A	29	A	0.138

[a] Different characters indicate significant differences (within one column) on 5% level according to the Tukey test.

after treatment of potato starch at 100 °C and 30% moisture for 16 h. They suggested that this effect was caused by changes in the packing arrangements of the starch crystallites and/or interactions between starch components in the amorphous regions of the granule during hydrothermal treatment.

C^* values were higher after treatment. Thus, as a consequence of the strong decrease in swelling power caused by the hydrothermal treatments, higher starch concentrations were needed to fill up the total space available for equilibrium swelling.

It is not clear why the different conditions applied during the hydrothermal treatments depressed AML, S, and SP to different degrees. No direct relationship was found between temperature and/or moisture content during treatment and the extent of the effect on AML, S or SP, and thus on C^*. However, hydrothermal treatments with highest impact on SP (i.e. treatments at 25, 30, and 35% m.c., Table 4) also led to the highest increase in gelatinization temperature [35]. Thus, the molecular changes induced by hydrothermal treatments that cause the decrease in swelling probably also cause the increase in gelatinization temperature. Possible molecular mechanisms proposed for these effects include: (i) transformation of amorphous amylose into a helical form [9]; (ii) an increase in interactions between amylose chains and/or between amylose and amylopectin chains in the amorphous regions, resulting in a decrease in the destabilizing effect exerted by the amorphous regions on the melting of the starch crystallites during gelatinization [15]; (iii) alterations in the interaction between crystallites and the amorphous matrix [5].

The results for G' (and G'') of the native and the hydrothermally treated starches can be explained when distinguishing different concentration regimes of the swellable (starch) particles [28]. Indeed, at low concentrations, the gel particles are completely swollen [Fig. 3(a)]. At a higher starch concentration the fully swollen granules just fill up the available space [Fig. 3(b)]. This space filling concentration is also referred to as the close packing concentration C^*. At high concentrations the granules cannot swell to their equilibrium volume since water availability is limited [Fig. 3(c)].

At low concentrations, i.e. when the starch concentration C is much lower than the close packing concentration C^* (i.e. C/C^* less than unity), the rheological properties are mainly determined by the volume fraction of the particles and to a lesser extent by the soluble fraction [28]. Thus, in this concentration regime, starches with the highest swelling power are the most viscous and show the highest storage modulus (G') at a given concentration [28]. At concentrations above C^* (i.e. C/C^* above unity), the system is completely filled with swollen starch particles and the rheological properties are mainly determined by the particle rigidity of the swollen granules.

Table 3
Storage moduli (G'), loss moduli (G''), and loss tangents (tan δ) of 3% gels of native and hydrothermally treated starches

Treatment	G' (Pa)		G'' (Pa)		Tan δ
None	22	A B [a]	7	A [a]	0.318
20% m.c., 105 °C	24	A	8	A	0.333
25% m.c., 97 °C	0	D	0	C	–
30% m.c., 90 °C	15	B C	7	A D	0.466
35% m.c., 84 °C	2	C D	1	C D	–
40% m.c., 52 °C	35	A	12	B	0.343

[a] Different characters indicate significant differences (within one column) on 5% level according to the Tukey test.

Table 4
Amylose leachings (AML), solubilities (S), swelling powers (SP), and close packing concentrations (C^*) of native and hydrothermally treated starches, determined after gelatinization under low shear conditions

Treatment	AML (%)		S (%)		SP (g/g)		C^* (%)
None	16	A [a]	16	A [a]	122	A [a]	1.0
20% m.c., 105 °C	5	B	6	B	37	C	3.1
25% m.c., 97 °C	3	B	3	B	9	D	10.2
30% m.c., 90 °C	6	B	6	B	22	C D	5.1
35% m.c., 84 °C	5	B	6	B	15	D	8.3
40% m.c., 52 °C	13	A	13	A	71	B	1.6

[a] Different characters indicate significant differences (within one column) on 5% level according to the Tukey test.

The particles flow more easily past each other, as they are more deformable (i.e. when their swelling power is higher) [28]. Therefore, starches with the lowest swelling power, or highest rigidity are the least deformable and have the highest storage moduli, in contrast with what holds for the dilute concentration regime.

With the above in mind, the results obtained for G' (and G'') of the native and the hydrothermally treated starch can be explained. Based on the C^* values (Table 4), we can distinguish two starch sample groups. A first group consists of those in the concentrated regime i.e. when the starch concentration in the gel is above C^*, and a second one of those in the dilute regime with a starch concentration below C^*.

For the 20.0% starch gels all starches are in a concentrated regime since 20% is far above their C^* values ($20.0/C^* > 1$). Therefore, G' values are determined by the rigidity of the granules: accordingly, G' increases with decreasing swelling power. The order of the G' values indeed follows the inverse order of the swelling power (SP) as shown in Fig. 4.

For the 6.6% starch gels, native starch and the starches treated at 20, 30, and 40% moisture are in

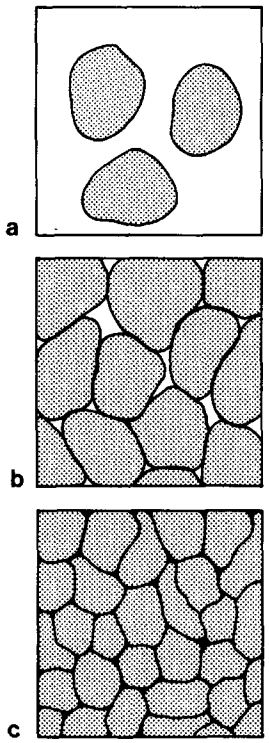

Fig. 3. Different concentration regimes of the starch granules: (a) completely swollen granules at low starch concentration ($C/C^* < 1$); (b) swollen granules just filling up the available space at the close packing concentration ($C = C^*$); (c) limited swelling of the particles at high starch concentrations ($C/C^* > 1$).

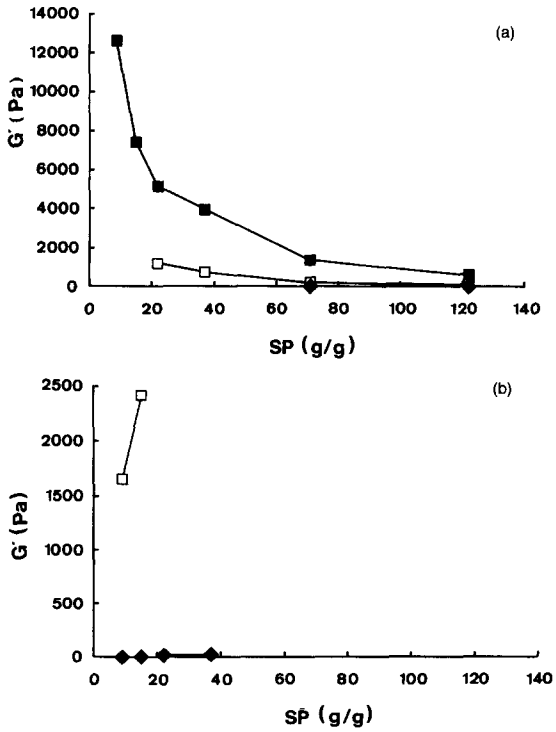

Fig. 4. Storage moduli (G') of starch gels of 3.0% (◆), 6.6% (□), and 20.0% (■) starch, as a function of swelling power (SP) of native and hydrothermally treated potato starch: concentrated regime (a) and diluted regime (b).

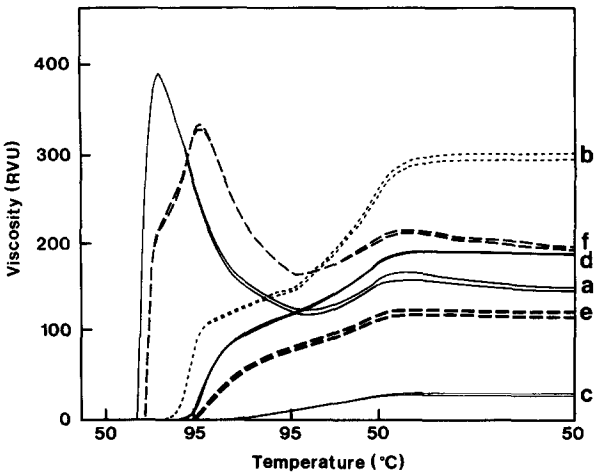

Fig. 5. RVA viscosity curves (RVU = rapid visco units) of 6.6% native and hydrothermally treated starch suspensions. Native starch (a); and starch hydrothermally treated at 20% m.c., 105 °C (b); 25% m.c., 97 °C (c); 30% m.c., 90 °C (d); 35% m.c., 84 °C (e); and 40% m.c., 52 °C (f).

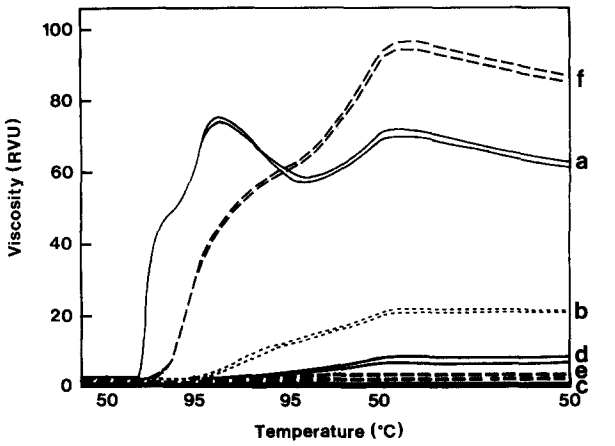

Fig. 6. RVA viscosity curves of 3.0% native and hydrothermally treated starch suspensions. Native starch (a); starch hydrothermally treated at 20% m.c., 105 °C (b); 25% m.c., 97 °C (c); 30% m.c., 90 °C (d); 35% m.c., 84 °C (e); and 40% m.c., 52 °C (f).

the concentrated regime ($6.6/C^* > 1$). For these starches we indeed observe an increase in G' with decreasing swelling power (Fig. 4) i.e. G' values show the following order: native < (40% m.c., 52 °C) < (20% m.c., 105 °C) < (30% m.c., 90 °C). The starches in the diluted regime ($6.6/C^* < 1$), show the opposite order. Thus G' increases with increasing swelling power of the starch, i.e. G' values of (25% m.c., 97 °C) < (35%, 84 °C).

In the case of the 3.0% gels only the native starch and the starch treated at 40% m.c., 52 °C are in the concentrated regime in contrast with the other starch samples. The same theory can be applied to explain the order of the G' values in both concentration regimes as explained above.

RVA viscosity properties.—Fig. 5 shows RVA viscosity curves of 6.6% native and hydrothermally treated starch suspensions. Treated starches showed an increase in viscosity development onset temperature and a decrease in peak viscosity. The extent of the effects depended on the treatment. End viscosities were lower after treatment at (35% m.c., 84 °C) and (25% m.c., 97 °C), and higher after treatments at (20% m.c., 105 °C), (40% m.c., 52 °C), and (30% m.c., 90 °C).

Fig. 6 shows the viscosity curves of 3.0% starch suspensions. Viscosity values were, in all cases, lower than the corresponding viscosity values of the 6.6% suspensions because of the lower starch concentration. As was the case for the 6.6% suspensions, treated starches showed an increase in viscosity development onset temperature and a decrease in peak viscosity. The extent of the effects depended on the treatment. In contrast with the 6.6% suspensions, end viscosity was only higher after treatment at (40% m.c., 52 °C) and lower after all other treatments. These findings are in agreement with those of Stute [5] who analyzed hydrothermally treated potato starch (at 20% moisture at 110 °C and 120 °C or at 83% moisture at 52 °C) with the Brabender amylograph.

Table 5
Solubilities (S), swelling powers (SP) and close packing concentrations (C^*) of native and hydrothermally treated starches, determined after gelatinization under high shear conditions

Treatment	S (%)		SP (g/g)		C^* (%)
None	17	A [a]	166	A [a]	0.7
20% m.c., 105 °C	11	B	49	B	2.2
25% m.c., 97 °C	6	B	18	C	5.9
30% m.c., 90 °C	11	B	37	D	3.1
35% m.c., 84 °C	11	B	32	D	3.6
40% m.c., 52 °C	19	A	116	E	1.1

[a] Different characters indicate significant differences (within one column) on 5% level according to the Tukey test.

Since we also wanted to correlate the RVA viscosity data with S, SP, and C^*, we modified both methods slightly in order to obtain more comparable conditions for both analyses. A quick cooling step up to 20 °C (temperature–time profile 2) was performed in the RVA instead of slower cooling to 50 °C (temperature–time profile 1) and starch samples were gelatinized in the RVA instead of in a bath with boiling water for analysis of S, SP, and C^* values. Profiles were very similar to the curves obtained after slow cooling, except for the end viscosity. End viscosity values were increased with ca. 66% after a

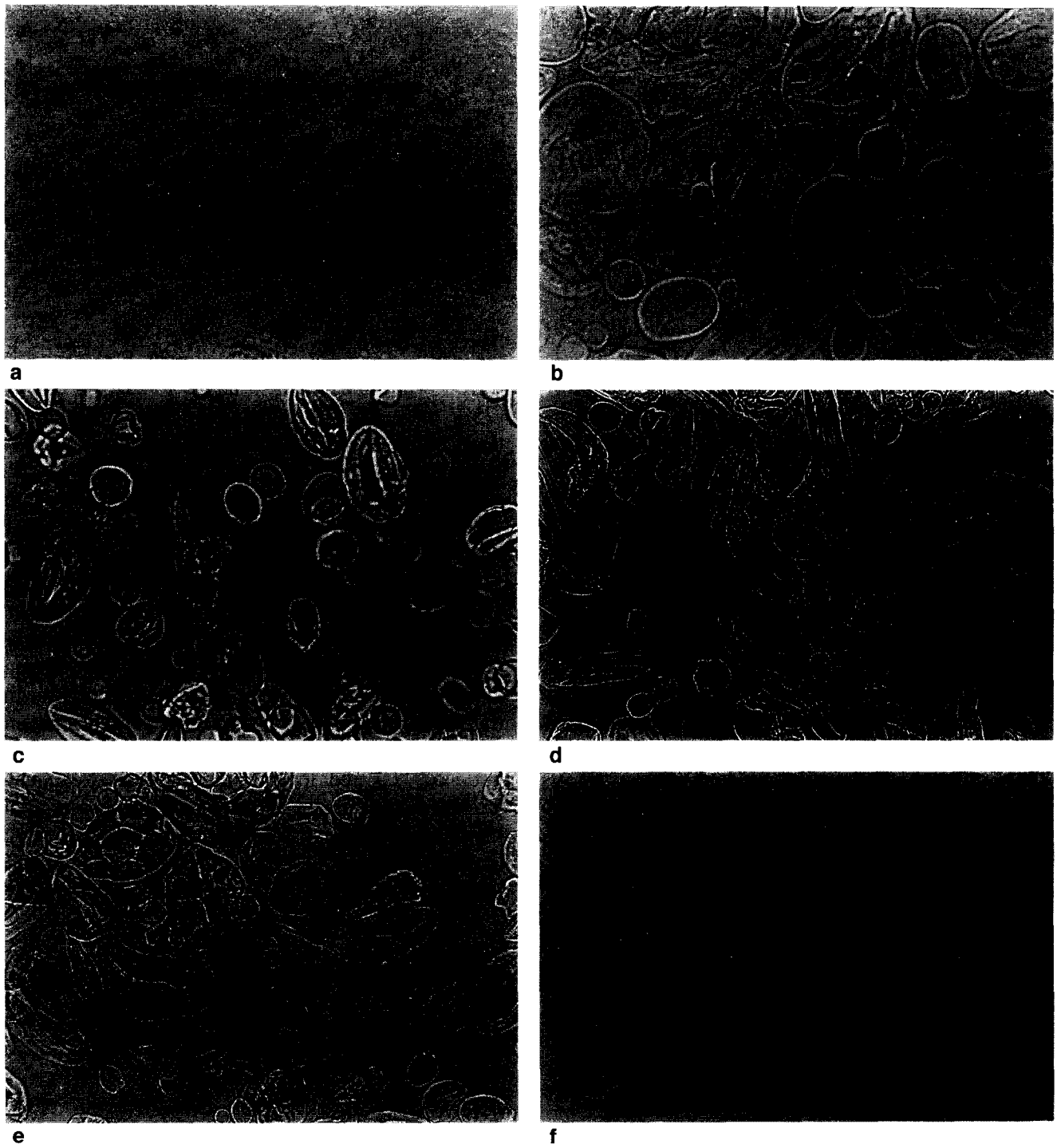

Fig. 7. Photomicrographs of 3.0% starch suspensions after the end of the RVA cycle: native starch (a); hydrothermally treated starch at 20% m.c., 105 °C (b); 25% m.c., 97 °C (c); 30% m.c., 90 °C (d); 35% m.c., 84 °C (e); and 40% m.c., 52 °C (f).

quick cooling step to 20 °C, but no changes in the order were observed. Table 5 shows S, SP, and C^* values of the starch samples determined after gelatinization under high shear conditions i.e. in the RVA. Swelling power and solubility were higher after high shear conditions than after low shear conditions (Tables 5 and 4, respectively) but the order of the effect of hydrothermal treatment was maintained.

Thus, peak viscosity readings were lower after all hydrothermal treatments investigated and for both concentrations (3.0% and 6.6%). The decrease followed the same order as the decrease in SP and S (Table 5), although differences in the latter were less clear. Indeed, it has been demonstrated that granule swelling and the amount of solubilized starch are the main factors in determining the viscosity during pasting [20,24]. Thus, viscosity values decrease when swelling of the starch granules is less pronounced and when less starch is solubilized.

The order in the observed end viscosities cannot be explained based on SP and C^* values (Table 5). This may be due to the impact of high shearing during the gelatinization and measurement in the RVA. Shearing has a tremendous effect on the swollen potato starch granules. It influences solubility, close packing concentration but also granule fragmention [19,21,24].

Photomicrographs.—Immediately after RVA analysis of 3.0 and 6.6% starch suspensions, photomicrographs were taken. From Fig. 7 (3.0% starch mixtures) it is obvious that hydrothermal treatments had a great impact on swelling power and rigidity of the starch granules. Granules were more intact and less swollen when hydrothermally treated. The impact of the treatment at 40% moisture at 52 °C was less intense. Similar results were obtained for the 6.6% mixtures and results are in agreement with swelling power values (Table 4).

4. Conclusions

In this study, potato starch was stored for 16 h at moisture levels varying from 20 to 40% and at temperatures 3% below the peak gelatinization temperature (K). Treatments greatly affected the rheological properties of the starch as analyzed with RVA and Bohlin rheometry for 3.0, 6.6, and 20.0% suspensions. The extent of the observed effects not only depended on the specific treatment but also on the concentrations investigated and the techniques used (static rheometry, high shearing e.g. RVA; or dynamic rheometry, low shearing e.g. Bohlin). With regard to the dynamic measurements, the extent to which the elastic moduli (G') of the gels was affected could be explained for all starch concentrations investigated, in terms of swelling power, close packing concentration and the starch concentration used. Hydrothermal treatment decreased amylose leaching, solubility and swelling power, but increased the close packing concentration. RVA measurements revealed an increase in the viscosity development onset temperature and a decrease in peak viscosity. This was also attributed to the decrease in swelling power and solubility after treatment. The impact of hydrothermal treatments on the end viscosities could not be related to the decrease in solubility, swelling power or the increase in close packing concentration. This may be due to the high shearing conditions in the RVA.

To date, plausible molecular mechanisms have been suggested to occur during hydrothermal treatment (see above [5,9,14,15]), but none of them has been proven yet. Therefore, it is not fully understood what molecular changes in the granules cause the decrease in swelling power and solubility, and the increase in rigidity. Although the effect of hydrothermal treatment on the G' values can be explained based on the swelling power, close packing concentration and starch concentration, it is not possible to predict readily the intensity of the effect of the hydrothermal treatment on the rheological properties. No direct relationship could be found between temperature and/or moisture content during treatment and the extent of the effect on swelling power or solubility. Further research is needed to increase our insight into the effects of hydrothermal treatments on a molecular level.

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