Extrusion Cooking and Drum Drying of Wheat Starch. II. Rheological Characterization of Starch Pastes[1]

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ABSTRACT

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Native wheat starch was processed by twin-screw extrusion cooking under five operating conditions, varying feed moisture (19–44%), and barrel temperature (90–180° C). These were compared to two drum-dried starches prepared by industrial processing. Functional properties were assessed from swelling capacities, viscographic patterns, and flow properties, which allowed the cold water behavior, the pasting characteristics, and the paste rheology to be estimated. The cold water behavior and the pasting pattern below 85° C were mainly ascribed to macromolecular entanglements in the solid-phase structure. Extruded samples, except for one processed at pasta-like conditions, exhibited lower cold water swelling and higher solubility

than drum-dried starches. This was ascribed to easier disentanglement of macromolecules resulting from starch depolymerization. The hot paste rheology of dispersions heated above 90° C was directly related to the overall macromolecular characteristics as determined by intrinsic viscosity. From viscograms and flow measurements, a transition-like phenomenon was evident within the range 85–90° C. Although extrusion cooking led to much thinner pastes than drum drying, some similar behaviors were observed under specific conditions, for example with high feed moisture and low extrusion temperature.

Extrusion cooking and drum drying are two industrial processes leading to the breakdown of starch granules. Such treatments produce significant ultrastructural changes, and cold water absorption as well as cold water solubility are increased. These properties are the basis of many applications, particularly for "instant starch slurries" in the food industry. In a previous paper, a comparison between both processes was reported with respect to structural and macromolecular starch modifications (Colonna et al 1984a). Each treatment leads to amylose and amylopectin depolymerization by random chain splitting, and the extent of this modification of each starch fraction depends on the type of treatment. Thus, the average molecular weight of amylose decreased by factors of 1.1 and 1.5 for a drum-dried sample and an extruded one, respectively, whereas average molecular weights of amylopectin were decreased by factors of 2.6 and 15. Moreover, water-soluble fractions (WSF) of drum-dried samples were reported to be enriched with amylose, whereas WSF of extruded samples maintained the same amylose/amylopectin ratio as in native starch. These rather different effects of both processes should lead to specific functional properties. Although there are ample reports in the literature concerned with this aspect of extruded starches (Lawton et al 1972, Mercier and Feillet 1975, Linko et al 1981, Gomez and Aguilera 1984) and on drum-dried, starch-based products (Powell 1967; Anderson et al 1969a,b; Anderson 1982), little published information exists on the

comparative differences between the two processes. Only for cereal grits has a comparison been published (Anderson et al 1969a,b, 1970; Anderson, 1982). Some authors have used drum-dried starches to represent 100% gelatinized starch as a reference in estimating the degree of cooking or degree of gelatinization of extruded products (Paton and Spratt 1981; Gomez and Aguilera, 1983, 1984).

Among the different methods used to estimate functional properties of such starch-based products, viscographic methods are the most widely described. Pasting behavior is easily characterized after a cooking and cooling procedure. However, an accurate estimation of rheological characteristics cannot be obtained with such empirical methods, and basic rheological methods must be used. Recently some authors reported on the flow behavior of extruded starch pastes by taking measurements with coaxial cylinder viscometers (Launay and Lisch 1983, Fletcher et al 1984, Launay and Koné 1984, Koné 1984, Colonna et al 1984b). However, these data were not compared to measurements for drum-dried starches, and interpretation by reference to structural characteristics such as solid-phase structure and depolymerization during processing was limited.

The objectives of this work were to compare functional properties of thermally modified starches processed by extrusion cooking and drum drying and to relate these properties to structural parameters described in the previous paper (Colonna et al 1984a).

MATERIALS AND METHODS

Starch
Prime wheat starch, with a moisture content of 13.9%, was obtained from Roquette Frères (F. 62136, Lestrem, France).

Drum Drying and Extrusion Cooking
Starch was extruded with a twin-screw Creusot-Loire extruder

(model BC-45) with 500-mm screws. A module with a reverse flight was located on the terminal position of each screw, just before the two dies of 50-mm length and 4-mm diameter. Four samples (LM-LT, hM-LT, hM-hT, LM-hT) were prepared at two temperatures (125–130°C [LT] and 180°C [hT]) and two moisture contents (20%, LM; 25%, hM). Another sample was extruded with a higher moisture content (45%) at low temperature (90°C) and was designated as pasta-like (PA). Details on operating conditions for extrusion are described in the previous paper (Colonna et al 1984a). Two drum-dried starches, D1 and D2, were prepared with a monoroll cooker rotated at 10 rpm and heated by steam at a pressure of 10 bars (180°C). The starch slurry, containing 450 g of starch per liter of water, was directly dried in the first assay (D1) or first precooked and dried in the second assay (D2).

Swelling Capacity

Exactly 500 mg of finely ground (less than 100 μm) sample was weighed in a centrifuge tube and mixed with freshly distilled water (50 ml) at room temperature. The suspension was homogenized by magnetic stirring in a water bath at 25 or 50°C for 30 min. After centrifugation at 3,000 $\times$ g for 10 min, the sediment was weighed and its water content determined by drying at 130°C for at least 2 hr to constant weight.

Viscographic Method

The viscographic test was carried out with a Brabender Viscograph E using the 250-cmg sensitivity range. Starch slurries were prepared by dispersing ground samples in freshly distilled water while stirring. Starch suspensions (485 g) were then transferred to the viscograph, heated from 30 to 96°C (heating rate, 1.5°C/min), held at 96°C for 15 min, and then cooled to 30°C. Consistency and temperature profiles were simultaneously recorded. Concentrations were chosen to be within the sensitivity range of the measuring system, namely 6% for drum-dried D1 and D2 and extruded PA and 10% for the other extruded samples.

Pasting Procedures

Two pasting procedures were compared by viscometry. The first was characterized by a low heating rate (1.5°C/min) using the Viscograph as a cooking device. The second procedure was carried out with a high heating rate (average rate, 6°C/min) and low agitation (Doublier 1981). In the second procedure starch slurries were heated from 30 to 96°C in a double-walled, round bottom vessel, and the maximum temperature was held for 30 min. Stirring was achieved by an anchor-shaped blade rotating at 200 rpm. Starch concentrations were within the range 5–9.5% (w/w).

For both procedures, pasted starch dispersions were hot-filtered through sintered glass in order to avoid clumps. Starch pastes were then rapidly degassed under vacuum to remove air bubbles. Starch concentrations were determined by drying aliquots overnight at 103°C.

Viscosity Measurements

Viscosity was measured with a coaxial-cylinder viscometer (Rheomat 30 Contraves, Zurich) with the following specifications

for the cylinders: internal radius, 22.9 mm; external radius, 24.2 mm; and height, 56.5 mm. Measurements were made either at 60 or 30°C on freshly prepared starch pastes. Each sample was submitted to a shear rate scan from 0 to 662 S^{-1} and back to 0 S^{-1}, at the same rate of 331 S^{-1}/min. The time-dependency (thixotropy) could be estimated when a loop was obtained between the "up" and "down" curves. The same sample was then submitted to shear rates decreasing step by step from 662 to about 1 S^{-1}; each step was maintained for the time needed to reach an equilibrium of the shear stress, always less than 20 sec. This procedure allowed the apparent viscosity to be measured with accuracy over almost three decades of shear rates (from approximately 1 to 662 S^{-1}).

RESULTS

Swelling Capacity

Cold swelling capacity at 25 and 50°C was lower (3.9–9.2 g·water/g·dry sediment) for extruded starches than for drum-dried starches (15.2–16.3 g) (Table I). Increasing the temperature from 25 to 50°C did not significantly change these values, which is in agreement with data previously reported (Anderson et al 1969a,b, 1970; Conway 1971; Mercier and Feillet 1975).

Viscosity Patterns: Pasting Behavior

Viscograms of 6% dispersions of D1, D2, and PA (Fig. 1) and of 10% dispersions of LM-LT, hM-LT, hM-hT, and hM-LT (Fig. 2) had hot paste consistencies of the same order, so the overall consistency profiles could be compared. The viscogram of PA was very peculiar, being characterized by a low consistency at low temperature, a continuous increase until about 90°C with a shoulder between 65–80°C, and a sharp decrease above 90°C. The other curves, for D1, D2, and the four other extruded samples, displayed a continuous decline from 50 to 96°C. These six consistency profiles were characterized by a sharp decrease in the range 90–95°C with an inflection point. Table II shows different values taken from these consistency profiles, namely consistency at 50°C on heating (H) and on cooling (C), consistency at the end of the 96°C plateau (P), and temperature at the inflection point. As expected from the concentrations chosen, P values were of the same order of magnitude, corresponding to the sensitivity range of the viscograph. The ratio H/C was less than 1 for three extruded samples (LM-LT, hM-hT, and LM-hT) and much greater than unity for hM-LT, D1, and D2. The same classification can be drawn from the comparison of H to P: the ratio H/P was between
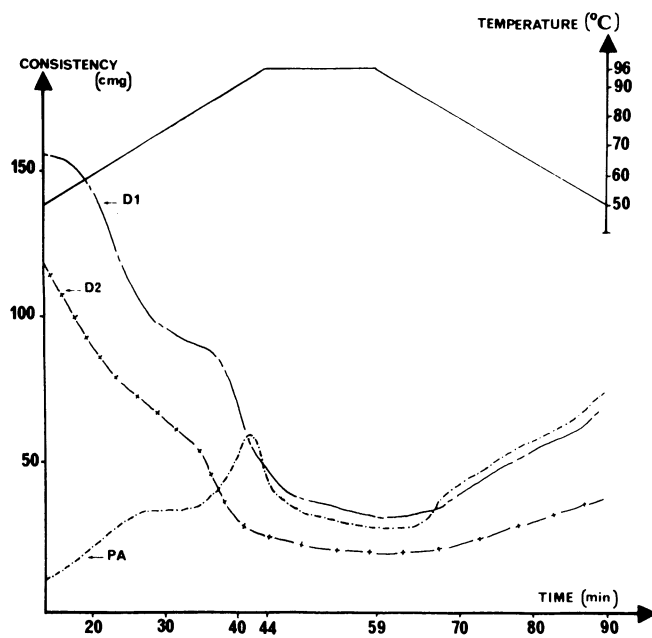
TABLE I
Swelling Power of Modified Starches
(grams of water per gram dry sediment)

Process	25°C	50°C
Extrusion cooking[a]		
LM-LT	4.7	4.6
hM-LT	9.2	6.1
hM-hT	5.1	5.5
LM-hT	4.3	3.9
PA	7.8	9.2
Drum drying		
D1	15.6	15.2
D2	16.3	15.2

[a]L = low, h = high, M = moisture, T = temperature, and PA = pasta-like sample.

Fig. 1. Viscograms of drum-dried starches (D1 and D2) and a pasta-like sample (PA). Concentration: 6%.

2.4 and 3.4 for the first three and between 4.5 and 7.1 for the three others. On the other hand, the ratio C/P depended on the type of process: around 2.0 for drum-drying and 4.0–5.0 for extrusion. PA behaved in a different way indeed as expected from the consistency profile but, as shown by the ratio C/P, it seemed nearer to the drum-dried samples when heated at 96°C than to the extruded ones.

Hot Flow Behavior of Starch Pastes: Description of Flow Curves

This rheological evaluation was carried out within the concentration range 5–9.5%. Typical flow curves are shown in Figure 3 for 8% concentrations at 60°C. These curves are obtained by increasing and then decreasing the shear rate ($\dot{\gamma}$) and plotting shear stress (σ) versus shear rate ($\dot{\gamma}$) on normal scales. For each sample, a shear thinning (pseudoplastic) behavior was clearly displayed with a slight thixotropy. Plotting these flow curves in logarithmic scales produced the curves shown in Figure 4, with the apparent viscosity (η_a) as a function of $\dot{\gamma}$, η_a being defined as the ratio ($\sigma/\dot{\gamma}$). Such curves were linear between 20 and 662 S^{-1} and can be described with a power law equation:

$$\eta_a = K \, (\dot{\gamma}/100)^{a-1},$$

where K is the consistency number corresponding to η_a at 100 S^{-1}, this shear rate being in the medium shear rate range where linearity is observed, and a is the shear-thinning number ($a < 1$).
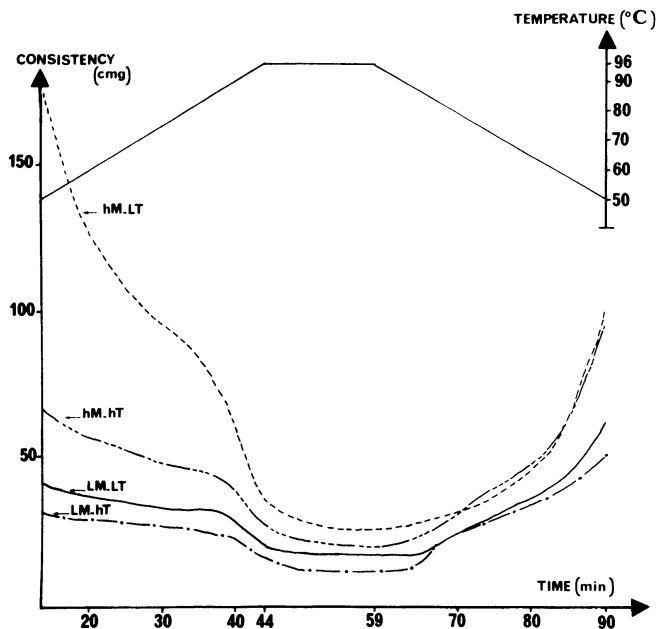
The viscosity order, D1 > PA > D2 > hM-LT > hM-hT > LM-LT > LM-hT, was the same as that obtained from the Viscograph.

Effect of Concentration

Within the concentration range investigated (5–9.5%), the flow curves can be described with a power law equation in the shear rate range 20–660 S^{-1}. For extruded samples, the exponent a decreased from 0.95 (nearly newtonian behavior) to 0.6–0.7 for increasing concentrations, whereas it varied from 0.7 to 0.6 for the drum-dried starches (Table III). The consistency number (K) displays linear
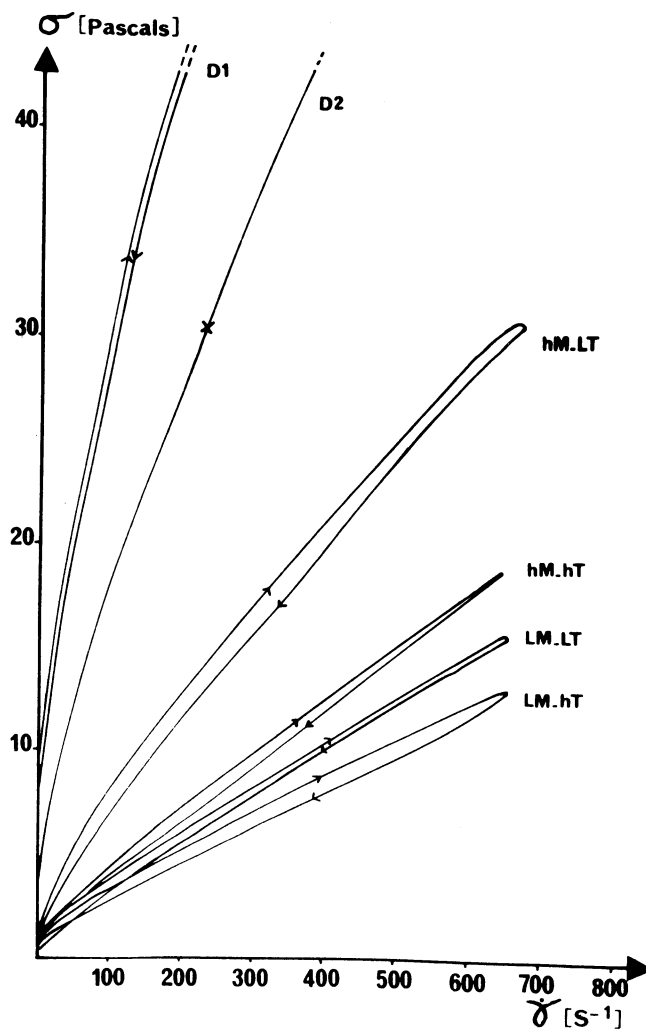
Fig. 3. Flow curves of starch pastes on linear scales (concentration: 8%, temperature: 60° C, heating rate: ~6° C/min).

Fig. 2. Viscograms of extruded starches: h, high; L, low; M, moisture; T, temperature. Concentration: 10%.

TABLE II
Viscograms: Comparison of Characteristic Parameters

Process	Consistency at 50°C on Heating, H (cmg)	Consistency at 96°C, P (cmg)	Transition Temperature (°C)	Consistency at 50°C on Cooling, C (cmg)	H/P	C/P	H/C
Extrusion cooking[a]							
LM-LT	42	17	93	62	2.38	3.70	0.68
hM-LT	180	26	90	100	6.92	3.85	1.80
hM-hT	68	20	93	100	3.45	5.00	0.68
LM-hT	32	12	93	51	2.67	4.35	0.63
PA	11	30	...	75	0.37	2.50	0.15
Drum drying							
D1	155	34	90	71	4.54	2.08	2.17
D2	146	20	93	41	7.14	2.04	3.57

[a]L = low, h = high, M = moisture, T = temperature.

variations with concentration for D1 and D2 with slopes of 3.3 and 3.7, respectively (Fig. 5). For PA, K variations were linear and comparable to D2 until 8%, but a sharp increase was observed above this value. Extruded samples also exhibited linear variations below 8% concentration, with slopes between 2.5 and 3 and rapid increases above 8%. The very large differences observed within the low concentration range decreased at the highest concentrations.

Effect of Pasting Parameters

A comparison of two pasting procedures is presented in Figure 6 for a drum-dried (D1) and an extruded starch (hM-hT). For the extruded one, pasting with the viscograph (1.5°C/min) led to a higher viscosity than rapid heating (30–90°C for 10 min), whereas a lesser effect was observed for D1. Table III compares K and *a* values of all samples at equivalent concentrations. Except for PA, preparation with a low heating rate led to a higher viscosity than with a high heating rate. When comparing pasting procedures, the K1/K2 ratio varied widely between samples, with a higher dependence for hM-LT, hM-hT, and LM-hT (>1.5) than for the others, LM-LT, D1, and D2 (<1.5). Thus for these six samples, a low heating rate led to a higher viscosity than a rapid heating rate, whereas the inverse was observed for PA and for a native wheat starch (Doublier 1981).

The effect of cooking temperature is illustrated in Figure 7. This parameter was investigated to complete observations on the sharp consistency decrease within the 90–95°C range (Figs. 1 and 2). Two pasting temperatures were chosen (70 and 96°C) on each side of this critical zone. At the end of the cooking period, the starch pastes

TABLE III
Effect of Pasting Procedures on Power Law Parameters

Process	Concentration (%)	Low Heating Rate[a] Viscosity[c] $K_1 \times 10^2$	*a*	High Heating Rate[b] Viscosity[c] $K_2 \times 10^2$	*a*	K_1/K_2
Extrusion cooking[d]						
LM-LT	8.7	4.9	0.81	3.63	0.82	1.35
hM-LT	8.7	8.91	0.73	5.89	0.77	1.51
hM-hT	8.6	10.5	0.68	4.47	0.80	2.35
LM-hT	8.6	7.24	0.72	4.17	0.78	1.74
PA	8.9	53.7	0.53	66.1	0.56	0.81
Drum drying						
D1	8.4	36.3	0.59	26.6	0.62	1.36
D2	8.6	26.9	0.62	21.9	0.61	1.23

[a] 1.5°C/min with the Brabender viscograph.
[b] Average rate of 6.0°C/min and slow agitation (200 rpm).
[c] Apparent viscosity measured at 60°C and at 100 S⁻¹, expressed in Pa × S.
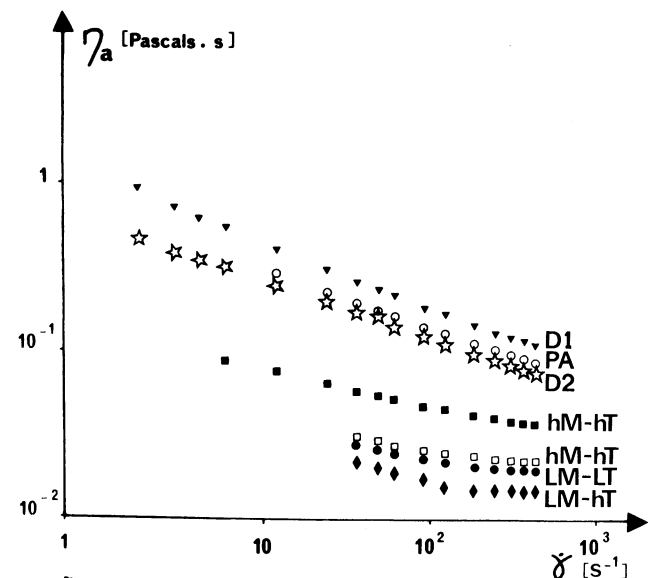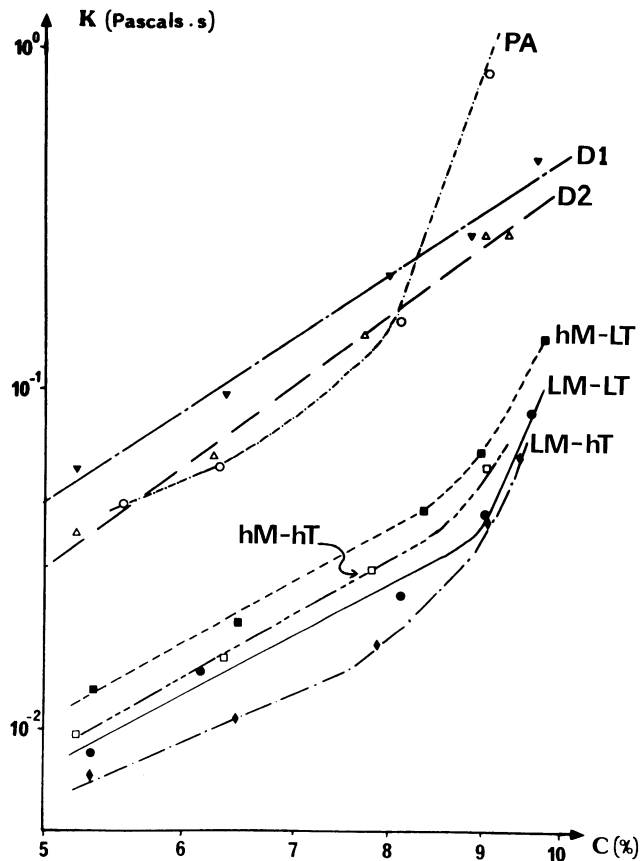[d] L = low, h = high, M = moisture, T = temperature, and PA = pasta-like sample.

Fig. 5. K variations as a function of concentration (logarithmic coordinates: temperature, 60°C; heating rate, ~6°C/min). **D1** and **D2**, drum-dried starches; PA, pasta-like sample. Extruded starches: h, high; L, low; M, moisture; T, temperature.

Fig. 4. Flow curves of starch pastes on logarithmic scales (concentration: 8%, temperature: 60°C, heating rate: ~6°C/min) **D1** and **D2**, drum-dried starches; **PA**, pasta-like sample. Extruded starches: h, high; L, low; M, moisture; T, temperature.
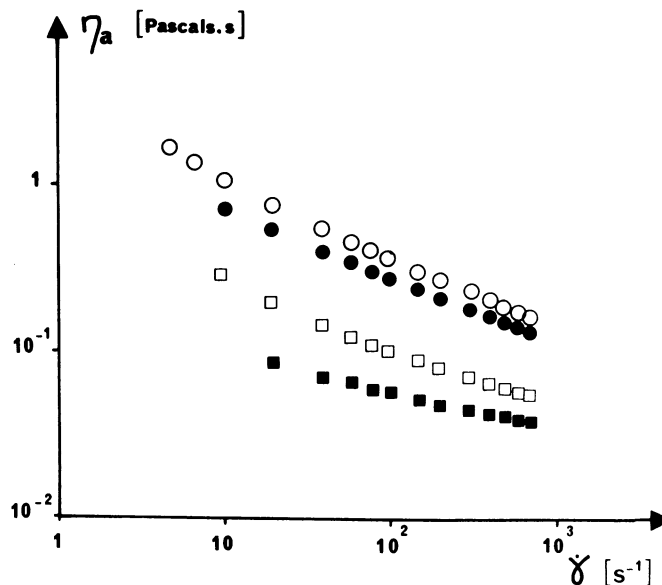

Fig. 6. Flow curves of an extruded starch (high-moisture, high temperature, hM-hT) and a drum-dried sample (D1). Effect of pasting procedure. Procedure with a low heating rate (Viscograph): O, D1;□, hM-hT. Heating rate ~6°C/min: ●, D1; ■, hM-hT. (Temperature, 60°C; concentration: 8.5%).

were rapidly cooled and characterized by their flow behavior at 30°C. The data obtained for one drum-dried (D1) and one extruded sample (hM-LT) with a 8.5% concentration are compared in Figure 7. It appears from the results in Table IV that all samples gave pastes more viscous when cooked at 96°C than at 70°C. However, the ratio is between 1.4 and 1.6 for drum-dried samples, whereas it varies from 1.8 to 2.2 for the extruded ones and is much higher for PA (3.3). Thus, despite the sharp consistency decreases exhibited within the range 90–95°C, the best efficiency from the rheological standpoint was achieved by cooking starch pastes at a temperature higher than 90°C.

DISCUSSION

Cold Water Behavior and Pasting Properties

Drum-dried starches were characterized by a high cold water swelling capacity when compared to the extruded ones. These data are in agreement with those of Gomez and Aguilera (1984) for drum-dried and extruded corn starch samples. Increasing temperature from 25 to 50°C did not significantly change the values in agreement with data reported previously (Mercier and Feillet 1975; Anderson et al 1969a,b, 1970; Conway 1971), which means that drum-dried starches are highly accessible to cold water. However, Colonna et al (1984a) reported that cold solubility of these samples is limited (14–25% at 25°C and 19–37% at 50°C). This can be related to the molecular weight of starch components, which are only slightly depolymerized and probably remain entangled inside a continuous matrix. For extruded starches, the relatively low water accessibility was combined with a high cold water solubility (60–80% at 25°C and more than 90% at 50°C) (Colonna et al 1984a). Both phenomena may be interpreted on the basis of starch-water interactions, which are also governed by the solid-phase structure of the processed starch as for extruded synthetic polymers (Porter and Casale 1985). The low water accessibility of extruded starches can be ascribed to a compact structure, whereas the solubility may be related to the lower molecular weight of starch components, which can be separated quite easily from each other owing to more limited entanglements. It may also be emphasized that drum-dried starches lead to water-soluble fractions enriched with amylose of lower molecular weights than in the original samples, in contrast to the extruded ones where no difference could be detected in this respect (Colonna et al 1984a). From the above, it can be seen that the cold water behavior

appears to be rather different between starches processed by these two methods. Drum drying leads to partial leaching of amylose during processing, whereas extrusion leads to starch melting and granule disruption without separation of amylose and amylopectin. Cold paste consistencies can be interpreted in a similar way. Thus D2 exhibits a lower H value than D1 (Table II) and this is easily explained by lower molecular weights of the starch components (Colonna et al 1984a). Both samples display much higher cold consistencies than extruded starches. This can be related to lower swelling capacities and lower molecular sizes of amylose and amylopectin, which are dramatically decreased by the extrusion process. However, quite similar cold consistency patterns were obtained for D2 and hM-LT despite the rather different concentrations (6 and 10%, respectively). This suggests that a similar cold water rheological behavior can be obtained by both processes in spite of quite different swelling-solubility patterns. On the other hand, PA displays a cold water behavior close to that of native starch but exhibits higher swelling capacities. Such peculiar characteristics might be useful in specific applications.

The overall pasting behavior was assessed from the viscographic pattern. The consistency decreased with increasing temperature (except for PA), which is the classical temperature dependence of the viscosity of suspensions. However, the sharp consistency decrease observed systematically around 85–90°C suggests that a structural transition occurs within this temperature range. The same abrupt decrease at approximately 90–96°C has been reported for extruded and for drum-dried starch-based products, but this feature has never been emphasized (Anderson et al 1969a,b, 1970; Anderson 1982; Kim and Rottier 1980; Gomez and Aguilera 1983; Kim 1984). Data obtained by Paton and Spratt (1981, 1984) with the Ottawa starch viscometer seem to display the same phenomenon. Existence of a transition within this temperature range is supported by the difference between flow curves for dispersions pasted at 70 and 96°C (Fig. 7 and Table IV), that is, below and above this transition zone, respectively. This transition occurs within the temperature range for the second swelling-solubilization stage of native cereal (Doublier 1981) and legume starches (Colonna and Mercier 1985). This stage is mainly characterized by a solubilization of some starch components, and it may be postulated that a partial solubilization of starch occurs within this temperature range for extruded as well as for drum-dried starches. This leads to a structural transition involving starch organization and distribution within the suspension. Thus, pasting thermally modified starches below 85°C would lead to rheological properties mainly related to the water absorption of solid particles, which would be mainly determined by the porosity of solid starch particles. On the other hand, pasting the same starches above 90°C would lead to a suspension where solubilized macromolecules are more involved, as reported for pasted native starches (Evans and Haisman 1979, Doublier 1981, Wong and Lelievre 1982).

The cooling behavior, as characterized by the C/P ratio (Table II), is rather different for the three types of thermally processed starches. The consistency increase from 96 to 50°C is twice as high
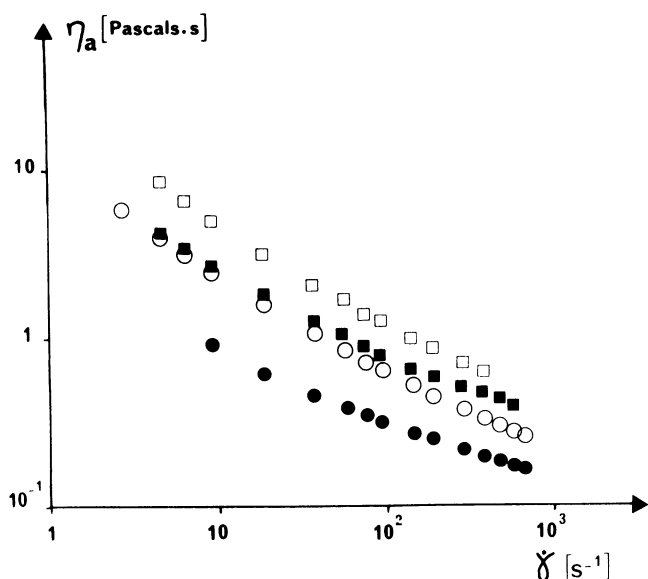

Fig. 7. Flow curves of an extruded sample (high moisture, low temperature, hM-LT) and a drum-dried sample (D1). Effect of pasting temperature, 96°C: □, D1; O, hM-LT; 70°C: ■, D1; ●, hM-LT. Temperature of rheological measurement: 30°C. Concentration: 8.5%.

TABLE IV
Effect of Pasting Temperature[a]

Process	K_{70} (Pa·S)	K_{96} (Pa·S)	K_{96}/K_{70}
Extrusion cooking[b]			
LM-LT	0.125	0.277	2.22
hM-LT	0.350	0.644	1.84
hM-hT	0.262	0.521	1.975
LM-hT	0.0861	0.169	1.962
PA	0.862	2.813	3.26
Drum drying			
D1	0.800	1.255	1.57
D2	0.550	0.765	1.39

[a] Viscosity measured at 30°C and at 100 S^{-1} (Concentration: 8.5%). Procedure with the Brabender viscograph.
[b] L = low, h = high, M = moisture, T = temperature, and PA = pasta-like sample.

for the extruded starches than for the drum-dried or pasta-like samples. Such a difference may be ascribed to starch structure, which might differ after pasting at 96°C. According to Paton and Spratt (1981), a comparison of up to down curves can be used for assessing the "degree of cook" of starches. In this respect, the H/C ratio (Table II) would be greater than 1 for fully cooked starches and less than 1 for partially cooked starches. On this basis, D1, D2, and hM-LT are fully cooked; LM-LT, hM-LT, and LM-hT are partially cooked to the same extent, and the degree of cook of PA is very low. Thus, based on the viscographic pattern and provided starch concentrations are sufficiently high (10% instead of 6%), consistency patterns of extruded starches may be comparable (hM-LT in this investigation) to those exhibited by drum-dried starches. A relation between H/C ratios (Table III) and K_{96}/K_{70} (Table IV) was also observed. This means that the degree of cook of thermally modified starches can be assessed by a viscographic method as well as by the K_{96}/K_{70} ratio.

Rheological Properties

The shape of flow curves in logarithmic scales does not differ basically from those reported for native cereal starch pastes (Evans and Haisman 1979, Doublier 1981, Wong and Lelievre 1982, Launay and Koné 1984) except that K values are lower and a values are closer to unity. From the shape of the flow curves, a slight upward curvature towards the low shear rates was observed for most curves, suggesting the existence of a yield stress, as observed for native (Evans and Haisman 1979, Wong and Lelievre 1982, Launay and Koné 1984) and extruded cereal starches (Launay and Lisch 1983). Such a tendency is generally displayed by suspensions of swollen particles in contrast to macromolecular solutions where a down curvature towards the low shear rate range is observed. Thus, whatever thermal process is used, it is confirmed that pasting thermally modified starches leads to suspensions of swollen particles dispersed in a macromolecular medium as for native starches. Size and volume fraction of these particles, as well as the size of solubilized macromolecules and their possible aggregation, will determine the resulting rheological properties. However, these characteristics are not easily estimated, and the respective roles of solubilized or aggregated macromolecules in the continuous medium and of the swollen particles in the dispersed phase could not be ascribed. Nevertheless, the concentration dependence of viscosities displayed by extruded samples is relatively small in the low concentration range compared to that of drum-dried starches (Fig. 5). The inverse is observed at concentrations above 8%. This suggests the flow behavior is not determined by the same parameters. Thus when K versus intrinsic viscosity, $[\eta]$, is plotted for each sample in logarithmic scales (Fig. 8), a linear variation is displayed by extruded starches. This suggests a close dependence of K on macromolecular characteristics, whereas the large difference in K for D1, D2, and PA for a low variation in $[\eta]$ may imply that the swollen particles are mainly involved for the latter three samples. Such a relation between hot paste viscosity and intrinsic viscosity has also been reported by Launay and Koné (1984) for extruded corn starches. These authors determined a limiting viscosity in a very low shear rate range (approximately $10^{-4} \cdot S^{-1}$), and this parameter was closely related to $[\eta]$ according to a power law with an exponent of 1, which should be compared to the slope of 1 displayed in Figure 8. Such an apparent discrepancy may be explained by the different shear rate ranges investigated: $10^{-4} \cdot S^{-1}$ against $100 \ S^{-1}$. As a rule, it is well known that slight differences in apparent viscosities observed at a relatively high shear rate can be largely magnified at very low shear rates.

CONCLUSION

Drum drying and extrusion cooking are two complementary thermal technologies that allow properties of starch to be varied over a wide range of functionalities. Although extrusion cooking and drum drying produce fully or partially cooked products, the identification of a phase transition in the pasting curves at around 85°C of the heating cycle necessitates heating such pastes to at least 90°C to ensure fully developed rheological characteristics.
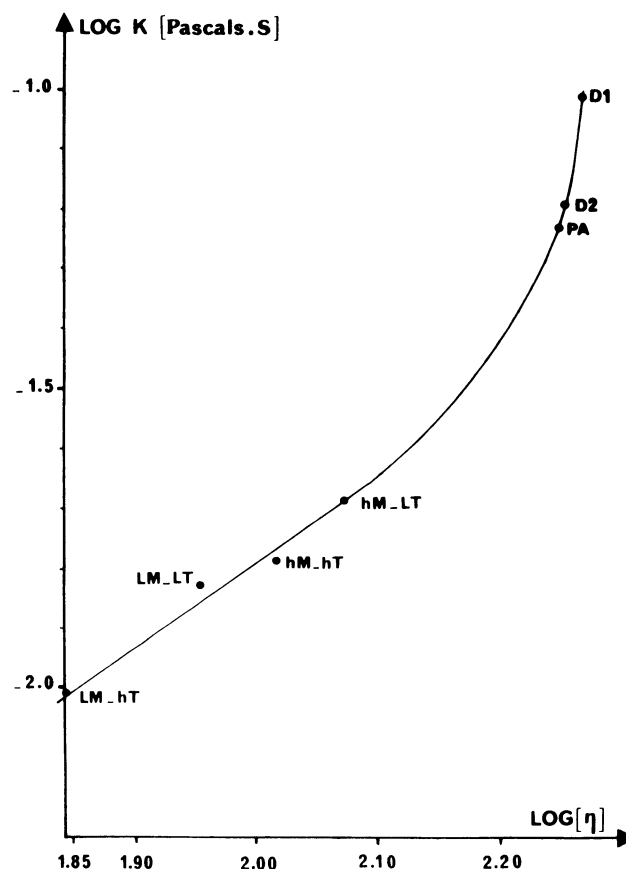

Fig. 8. Relation between K and the intrinsic viscosity of thermally processed starches. K values obtained from flow curves of 6% starch pastes prepared at 96°C. Temperature of rheological measurement: 60°C.

However, physicochemical aspects of this phenomenon are unknown and require further investigation. The overall rheological behavior should be interpreted in terms of starch paste structure. This requires a determination of the relative contribution and importance of the dispersed phase (swollen particles) and of the continuous phase (solubilized macromolecules). Data reported here in the concentration range 5–10% suggest that it is the solubilized macromolecules that are mainly responsible for determining the overall properties of extruded samples, whereas the behavior of drum-dried starches is primarily related to swollen particles.

LITERATURE CITED

ANDERSON, R. A. 1982. Water absorption and solubility and amylograph characteristics of roll-cooked small grain products. Cereal Chem. 59:265.

ANDERSON, R. A., CONWAY, H. F., PFEIFER, W. F., and GRIFFIN, E. L. 1969a. Gelatinization of corn grits by roll- and extrusion cooking. Cereal Sci. Today 14:4.

ANDERSON, R. A., CONWAY, H. F., PFEIFER, W. F., and GRIFFIN, E. L. 1969b. Roll and extrusion-cooking of grain sorghum grits. Cereal Sci. Today 14:372.

ANDERSON, R. A., CONWAY, H. F., and PEPLINSKI, A. J. 1970. Gelatinization of corn grits by roll-cooking, extrusion-cooking and steaming. Staerke 22:130.

COLONNA, P., DOUBLIER, J. L., MELCION, J. P., de MONREDON, F., and MERCIER, C. 1984a. Extrusion-cooking and drum-drying of

wheat starch. I. Physical and macromolecular modification. Cereal Chem. 61:538.

COLONNA, P., DOUBLIER, J. L., MELCION, J. P., de MONREDON, F., and MERCIER, C. 1984b. Physical and functional properties of wheat starch after extrusion-cooking and drum-drying. Pages 96-105 in: Thermal Processing and Quality of Foods. P. Zenthen, ed. Elsevier Appl. Sci.: London.

COLONNA, P., and MERCIER, C. 1985. Gelatinization and melting of maize and pea starches with normal and high amylose genotypes. Phytochem. 24:1667.

CONWAY, H. F. 1971. Extrusion-cooking of cereals and soybeans. Part 1. Food Prod. Dev. 4:14.

DOUBLIER, J. L. 1981. Rheological studies on starch: Flow behaviour of wheat starch pastes. Staerke 33:415.

EVANS, I. D., and HAISMAN, D. R. 1979. Rheology of gelatinised starch suspensions. J. Texture Stud. 10:347.

FLETCHER, S. I., McMASTER, T. J., RICHMOND, P., and SMITH, A. C. 1984. Physical and Rheological Assessment of Extrusion Cooked Maize. Pages 223-234 in: Thermal Processing and Quality of Foods. P. Zenthen, ed. Elsevier Appl. Sci.: London.

GOMEZ, M. H., and AGUILERA, J. M. 1983. Changes in the starch fraction during extrusion-cooking of corn. J. Food Sci. 48:378.

GOMEZ, M. H., and AGUILERA, J. M. 1984. A physicochemical model for extrusion of corn starch. J. Food Sci. 49:40.

KIM, J. C. 1984. Effect of some extrusion parameters on the solubility and viscograms of extruded wheat flour. Pages 251-256 in: Thermal Processing and Quality of Foods. P. Zenthen, ed. Elsevier Appl. Sci.: London.

KIM, J. C., and ROTTIER, W. 1980. Modification of aestivum wheat semolina by extrusion. Cereal Foods World 24:62.

KONÉ, T. 1984. Contribution à l'étude de la cuisson-extrusion de l'Amidon de mais, caracterisation des extrudats, propriétés rhéologiques des empois. Thèse de Docteur-Ingénieur. Université Paris VII.

LAUNAY, B., and KONÉ, T. 1984. Twin-screw extrusion-cooking of corn starch: Flow behaviour of starch pastes. Page 54-61 in: Thermal Processing and Quality of Foods. P. Zenthen, ed. Elsevier Appl. Sci.: London.

LAUNAY, B., and LISCH, J. M. 1983. Twin-screw extrusion cooking of starches: Flow behavior of starch pastes, expansion and mechanical properties of extrudates. J. Food Eng. 2:259.

LAWTON, B. T., HENDERSON, G. A., and DERLATKA, E. J. 1972. The effects of extruder variables on the gelatinisation of corn starch. Can. J. Chem. Eng. 50:168.

LINKO, P., COLONNA, P., and MERCIER, C. 1981. High-temperature, short-time extrusion cooking. Pages 145-235 in: Advances in Cereal Science and Technology, Vol. 4. Y. Pomeranz, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.

MERCIER, C., and FEILLET, P. 1975. Modification of carbohydrate components by extrusion cooking of cereal products. Cereal Chem. 52:283.

PATON, D., and SPRATT, W. A. 1981. Simulated approach to the estimation of degree of cooking of an extruded cereal product. Cereal Chem. 58:216.

PATON, D., and SPRATT, W. A. 1984. Component interactions in the extrusion-cooking process: Influence of process conditions on the functional viscosity of the wheat flour system. J. Food Sci. 49:1380.

PORTER, R. S., and CASALE, A. 1985. Recent studies on polymer reactions caused by stress. Polymer Eng. Sci. 25:129.

POWELL, E. L. 1967. Production and use of pregelatinized starch. Pages 523-536 in: Starch, Chemistry and Technology, Vol. 2. R. L. Whistler and E. F. Paschall, eds. Academic Press: New York.

WONG, R. B. K., and LELIEVRE, J. 1982. Rheological characteristics of wheat starch pastes measured under steady shear conditions. J. Appl. Polymer Sci. 21:1433.