Carbohydrate Polymers **13** (1990) 29–45

Shear Induced Changes in the Viscoelastic Behaviour of Heat Treated Potato Starch Dispersions

Karin Svegmark & Anne-Marie Hermansson

SIK, The Swedish Institute for Food Research, PO Box 5401, S-402 29 Göteborg, Sweden

(Received 15 April 1989; revised version received 29 June 1989; accepted 6 July 1989)

ABSTRACT

The viscoelastic behaviour of native potato starch dispersions was studied using dynamic viscoelastic measurements. The influence of various shear and heat treatments of gelatinized starch pastes were compared in the concentration range 4–10%. Heating had a minor effect compared to the effect of shear treatment. The complex modulus (G^*) decreased to about 5% of its maximum value when the starch pastes were sheared during the heating cycle, whereas heating alone resulted in a decrease to about 60% of the maximum G^* value. Shear also caused an increase in the phase angle and characteristic changes were observed with regard to frequency and strain dependencies. When samples were prepared in a Brabender viscograph, the shear induced changes took place early in the pasting cycle.

The characteristics of the concentration dependence differed due to the shear history of the sample. Peculiar concentration dependencies, some even negative, could be obtained from samples with different shear histories. The results imply that even moderate shear treatment gives rise to structure changes which are reflected by a transition in the type of the viscoelastic behaviour.

INTRODUCTION

The consistency and flow behaviour of starch dispersions are vital to their function in most applications. Starches are mainly used in foods because of their contribution to the texture of the products. Knowledge of how a certain consistency can be created or destroyed is of

Carbohydrate Polymers 0144-8617/90/$03.50 —

importance for the optimization of process conditions and in order to generate the desired properties in the product.

Viscoelastic measurements provide a tool for characterizing different types of consistency. The information given by dynamic viscoelastic measurements reflects the structure of a viscoelastic material more clearly than do results for viscometric investigations. In a viscosity test the deformations are so large that changes will be induced in the structure of most materials. These alterations, which can be either of a reversible or an irreversible nature, always influence the results and give rise to difficulties when evaluating viscosity tests. Dynamic viscoelastic tests, on the other hand, can be performed at such small deformations that effects on structures are negligible. Therefore viscoelastic parameters are useful for characterizing a material and the viscometry data provide information on how a material behaves during large deformations, e.g. during flow.

Quite a number of studies on starch pastes, using fundamental viscometric methods for determining the flow behaviour, have been published, see for example the review by Launay *et al.*, 1986. The flow behaviours of pastes prepared by different methods have been thoroughly investigated for wheat starch (Doublier, 1981; Wong & Lelievre, 1982; Doublier *et al.*, 1987), for maize starch (Doublier *et al.*, 1987) and for modified potato starch (Härröd, 1989). Almost all the methods of preparing wheat and maize starch pastes gave rise to flow curves with different characteristics (Doublier *et al.*, 1987).

Wong and Lelievre (1981) noted that the pasting procedure also influenced the viscoelastic properties of wheat starches. The viscoelastic properties of potato, maize and tapioca starch pastes, with regard to the effect of concentration, were studied by Evans and Haisman (1979). The changes in viscoelastic properties of wheat, potato, maize and waxy-barley starches during gelatinization were described by Eliasson (1986). The pH and ionic strength have proved to have an effect on the viscoelastic properties of potato starch systems but not on cassava starch systems (Muhrbeck & Eliasson, 1987). The shear stress relaxation of native and modified potato starches was studied by Bohlin *et al.* (1986).

In starch research the terms gelatinization and pastes are commonly used though the definitions may vary. The word gelatinization refers to the conversion of the starch granule from a semi-crystalline to a gelatinous form. The term gelatinization is in this paper used to describe this order–disorder phase transition of the starch granule which takes place when starch is heated in excess of water (Donovan, 1979). The transition is accompanied by the swelling and hydration of granules. The formation of starch pastes from starch suspensions is, here, defined by the changes in flow properties following the swelling of granules and the solubilization of starch molecules.

The Brabender viscograph is commonly used for characterizing the pasting properties of different types of starches. In this instrument the 'viscosity' is registered during heating, warm-holding and cooling. A major drawback is that the shear conditions in a Brabender viscograph are undefined. Root starches and especially potato starch give higher 'Brabender viscosity' initially after gelatinization compared with cereal starches. This has been attributed to a higher swelling ability for potato starches (Schoch, 1965). Further heating and stirring after gelatinization cause a decrease in viscosity which is most pronounced in potato starches. A rapid breakdown of swollen potato starch granules is simultaneous with the decrease in viscosity (Hofstee, 1962). Potato starch pastes change from a short to a long (cohesive) texture after heating and stirring (Osman, 1967).

In the present study the effect of shear is compared with the effect of heating at different concentrations for potato starch pastes using dynamic viscoelastic measurements. The aim is to map different types of consistency and to evaluate how the basic factors in the pasting procedure, i.e. time, temperature and shear history, influence the viscoelastic behaviour of potato starch pastes.

MATERIALS AND METHODS

Materials

A native potato starch was supplied by Stärkelsen (Karlshamn, Sweden) and had the following specifications: 19·9% water, 0·25% ash, 0·06% protein, 0·03% calcium, 0·07% phosphorus, less than 0·01% sodium; the pH in a 5% dispersion of starch in deionized water was 6·7; the diameter of a granule of average weight was determined to 45 μm.

The pasting curve of a 5% starch dispersion was determined with a Brabender viscograph (Fig. 1). The conditions for the Brabender consistency test are described in the following section.

Sample preparation

All samples were prepared in a Brabender viscograph. The starch was weighed and dispersed in distilled/deionized water. The starch–water suspension was stirred at 75 rpm. The total weight of the sample was

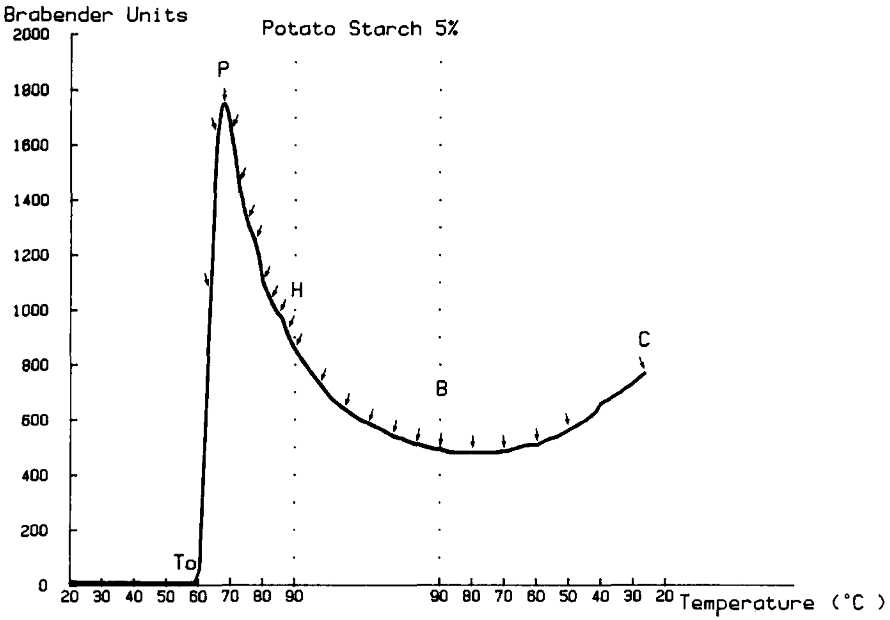

Fig. 1. The Brabender pasting cycle. The 'Brabender viscosity' of 5% potato starch expressed in Brabender Units at 700 cm g. The stages at which the pastes were transferred for viscoelastic tests are indicated as arrows. Pasting temperature (T_0), Peak viscosity (P), Hotpaste viscosity (H), Breakdown viscosity (B) and Coolpaste viscosity (C) are also marked.

450 g and the starch concentrations used were 4%, 5%, 8% and 10% by weight (3·2%, 4%, 6·4% and 8% by dry weight).

The temperature cycle was begun by heating from 35°C to 90°C at a rate of 1·5°C/min. The temperature was then held at 90°C for 30 min and finally the temperature was decreased to 25°C at a rate of 1·5°C/min.

Samples were transferred from the Brabender viscometer to the Bohlin VOR Rheometer at various stages to measure viscoelastic properties (see Fig. 1). Pastes transferred at Peak viscosity or earlier were defined as *low sheared.* Some shear is necessary before the onset of swelling in order to avoid sedimentation. The transfers were done as quickly as possible in order to minimize the temperature fall in the starch pastes.

Rheological measurements

A Bohlin VOR Rheometer was used in the oscillation mode. The dynamic measurements were performed at a frequency of 1 Hz and at a strain of $1{\cdot}5\times10^{-3}$. At this strain all samples were in the linear strain region. Sequential oscillatory measurements were made every 30 s. Measurements were made in the C 25 concentric cylinder measuring system (DIN 53019) and torque bars of 3·2 g cm and 18 g cm were used. The samples were covered with a thin layer of paraffin oil in order to avoid the drying out of the surface.

Two different kinds of temperature treatments were used:

Constant temperature. Starch pastes were transferred from the Brabender viscograph to the Bohlin Rheometer at different stages during the temperature cycle. These measurement points are shown in Fig. 1 as arrows. Each sample was measured in the Bohlin Rheometer at the same temperature at which it was taken from the pasting cycle.

Temperature cycle. Pastes were transferred either at Peak viscosity (P), at Hotpaste viscosity (H) or at Breakdown viscosity (B), (see Fig. 1). The temperature treatment continued in the Bohlin Rheometer, from the temperature of transfer, with the same cycle as that used in the Brabender viscograph (see Fig. 1). The temperature treatment used during the viscoelastic measurements was thus the same as in the Brabender viscograph but the shear influence was minimized.

After the temperature treatments previously described the frequency dependence of each paste was studied between 0·1 Hz and 10 Hz and finally the strain dependence was studied from 0·0003 to 0·1.

RESULTS AND DISCUSSION

Two independent parameters are obtained from dynamic measurements. The storage modulus (G') describes the part of the deformation energy stored in the material, i.e. the elastic response. The loss modulus (G'') describes the deformation energy lost, i.e. the viscous response. Another way of presenting the same results is through a complex modulus (G^*) and phase angle (δ) according to:

$$G^* = G' + \mathrm{i}G'' \qquad (\mathrm{i}^2 = -1) \tag{1}$$

$$\tan\delta = G''/G' \tag{2}$$

The complex modulus represents the shear resistance at small deformations. The phase angle gives information about the ratio of the elastic to the viscous response of the material. A low phase angle indicates a solid-like behaviour.

Changes in viscoelastic properties during the pasting cycle in the Brabender viscograph

Pastes, at a concentration of 5%, were prepared in the Brabender viscograph and transferred at different stages of the pasting cycle as illustrated in Fig. 1. The viscoelastic measurement was made at the same temperature at which the sample was taken from the Brabender.

The complex moduli of samples transferred at various points are shown in Fig. 2. The maximum value of the complex modulus was achieved at 65°C which is almost the same as that of the peak value of the 'Brabender viscosity'. Further treatment in the Brabender, after this maximum value, drastically lowered the complex modulus. A minimum plateau value was reached after holding at 90°C for 10 min. Thereafter continued heating and shearing had little effect. The minimum value of the complex modulus was 21 times lower than the maximum value at 65°C, the decrease in 'Brabender viscosity' during heating and stirring was at most 3·6 times as seen in Fig. 1. The 'Brabender viscosity' behaved differently compared with the complex modulus during warm-holding. The 'viscosity' continued to decrease throughout the warm-holding time, whereas the complex modulus reached a minimum plateau value of 10 Pa after 5–10 min of heating at 90°C.

The phase angles of the samples transferred from the Brabender are shown in Fig. 3. The phase angle was about 10° initially which means that the elastic response (G') dominates over the viscous response (G'').

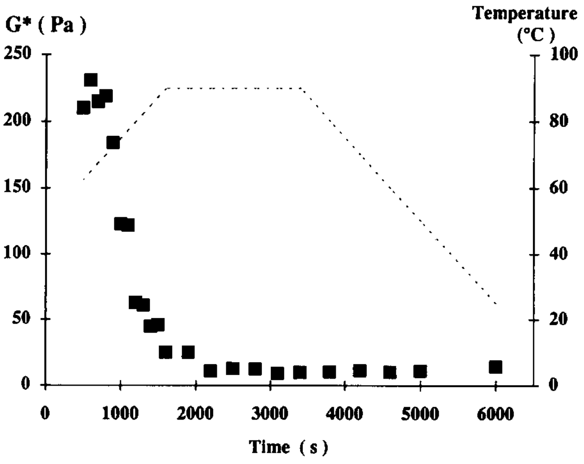

Fig. 2. Changes in the complex modulus (■) of 5% potato starch dispersions during the pasting cycle in the Brabender viscograph. The temperature of the Brabender pasting cycle is shown by the broken line.

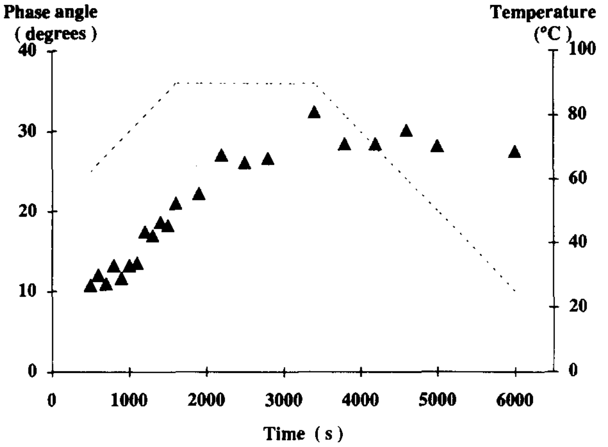

Fig. 3. Changes in the phase angles (▲) of 5% potato starch dispersions during the pasting cycle in the Brabender viscograph. The temperature cycle of the Brabender pasting cycle is shown by the broken line.

The low value of the phase angle indicates the existence of a network structure. When potato starch pastes were stirred and heated after gelatinization, the phase angle increased until it reached a final value of 30° after heating at 90°C for 10 min. At the same time *G** reached its minimum plateau value.

Temperature induced changes in viscoelastic properties of low-sheared pastes

To evaluate the effect of heating versus the effect of shearing, low-sheared pastes (transferred at Peak viscosity, see Fig. 1) were subjected to the same temperature cycle during dynamic measurements as in the sample preparation procedure. Generally, the structure breakdown caused by the shear forces applied by oscillatory measurements in the linear strain region can be considered to be negligible. The pasting cycle used during the dynamical tests was thus analogous to the Brabender pasting cycle except for the fact that the shear influence was omitted.

The effect of temperature treatment on the complex modulus can be seen as the continuous complex modulus curve in Fig. 4. The initial increase in *G** of the low-sheared paste was probably due to time-dependence. The complex modulus was lowered to about 55% of its maximum value during the heating of low-sheared pastes. The combined heat and shear treatment in the Brabender lowered the complex modulus to 5% of the maximum value, as shown by the squares in Fig. 4.

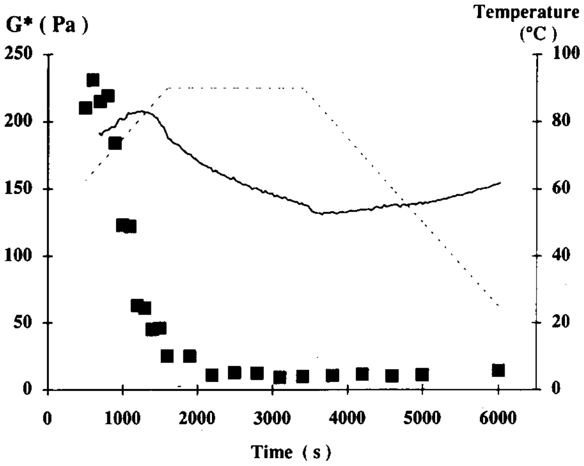

Fig. 4. Changes in the complex modulus of 5% potato starch pastes; low-sheared pastes (———) pastes prepared in the Brabender viscograph (■), temperature (...).

Since the temperature gradient was the same in both tests, it can be concluded that the drastic decrease in the complex modulus was caused by the shear treatment.

The temperature treatment had no impact on phase angles for low-sheared pastes. The phase angle was 11° at 67°C, 10° after heating at 90°C, and 11° after cooling to 25°C.

Characteristics of sheared and low-sheared pastes

The results shown in Figs 2–4 suggest that a new type of rheological behaviour for potato starch pastes can be the result of shear. The low-sheared pastes were characterized by a moderately elastic response ($\delta = 10°$) and a medium high shear resistance ($G^* = 100$–200 Pa). Heat treatment did not change these main characteristics. The type of behaviour exhibited by the low-sheared potato starch systems will hereafter be referred to as type I behaviour. When prepared in the Brabender this kind of behaviour was detected up to 75°C.

Further heating and shearing resulted in the transition to a less elastic state with higher phase angles and notably less shear resistance. The kind of behaviour caused by shearing with a phase angle of about 30° and a relatively low complex modulus (10 Pa), will be referred to as type II behaviour.

Typical type II behaviour was detected in all pastes after heating at 90°C for 10 min in the Brabender viscograph. The 'Brabender viscosity' continued to decrease after this point. So, the transformation in viscoelastic behaviour occurred earlier than indicated by the 'Brabender viscosity' curve. The shear induced decrease in G^* was higher than the decrease in 'Brabender viscosity'. Thus viscosity and complex modulus are not fully correlated for shear induced changes in potato starch systems. The shear induced structure breakdown strongly affects the elasticity and shear resistance at small deformations. Viscoelastic measurements are therefore more sensitive for detecting the nature of the shear induced structural breakdown than viscosity measurements.

The comparison of the changes in phase angles for sheared and low-sheared pastes reveals a shear induced effect on the structure. An almost constant phase angle throughout the time–temperature gradient in the viscoelastic measurements implies minor structural changes, whereas the increase in phase angles for sheared pastes clearly indicates a structure breakdown.

Strain dependence

Above a critical deformation structural breakdown occurs which causes a decrease in elasticity. All dynamic measurements were performed in the linear strain region. This is the region where the viscoelastic parameters are independent of the deformation. The low-sheared pastes, which have been characterized as type I, had a rather narrow linear region (up to 0·002 at 67°C). During the transformation to type II state, the linear region became larger and larger as can be seen in Fig. 5. Since G^* spans from 10 Pa to 200 Pa the results were normalized by dividing G^* by the constant value in the linear region, G^* (linear). Sheared pastes

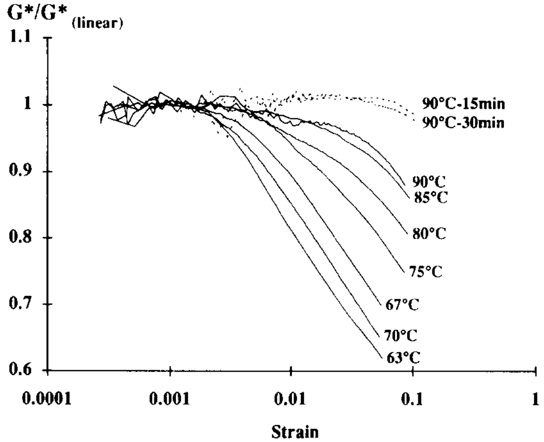

Fig. 5. The normalized complex modulus (G^*/G^*_{linear}) against strain in logarithmic scales. Pastes were transferred from the Brabender viscograph at the stages marked.

(type II behaviour) were practically strain independent in the region tested (0·0003 to 0·1). The measuring temperature influenced the strain dependence. Low-sheared (type I) pastes became less strain dependent when measured at temperatures lower than the temperatures shown in Fig. 5. It is therefore necessary to determine the linear strain region for a system at a relevant temperature.

The range of the linear region gives information about the material. Ross-Murphy (1984) generalized the strain dependencies for a colloidal dispersion, a biopolymer gel and for a biopolymer solution. Compared with these structure types, the strain dependencies of low-sheared pastes (type I) were similar to those of typical colloidal dispersions. Since the strain dependencies were reversible, and the phase angles were rather low the system can be considered as a weak colloidal network, a weak gel. This network may consist of interactions between the dispersed granules or by a network formation in the continuous phase. The character of the sheared samples (type II) was similar to typical macromolecular biopolymer solutions.

Frequency dependence

The frequency dependence of the shear modulus (G', G'') may also give valuable information about the structure. A material which is frequency independent over a large time scale range is solid-like and this can be used as a characteristic of true gel systems. Strong dependence suggests a structure with molecular entanglements which behaves more like a solid at high frequencies and more like a liquid at low frequencies (Ross-Murphy, 1984).

The frequency dependence of pastes at different stages of shearing during the pasting cycle in the Brabender, is shown in Fig. 6. The storage modulus has been normalized by dividing by the value of 0·1 Hz ($G'_{0\cdot1\ \mathrm{Hz}}$). The longer time the pastes were heated and sheared, the stronger the frequency dependence. This is in agreement with the postulated transformation from a type I state to a type II state through shear treatment. There seems to be good correlation between the changes in phase angles as shown in Fig. 3, and the changes in frequency dependence as shown in Fig. 6. The frequency dependence can be modelled by

$$\log G' = k + n \log w \tag{3}$$

The slope value (n) of this equation is a measure of the frequency (w) dependence (Egelandsdal *et al.*, 1986). The triangles in Fig. 7 show the relationship between phase angles and slope values of sheared and low-sheared pastes at a concentration of 5%. When correlating the phase

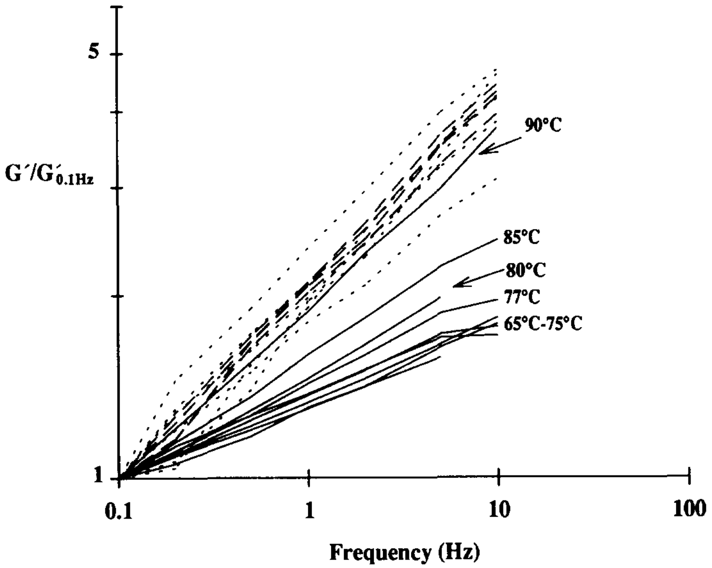

Fig. 6. Frequency dependence of the storage modulus expressed by ($G'/G'_{0\cdot1\,\mathrm{Hz}}$). Pastes were transferred from the Brabender during heating at 65–90°C (———), during heating at 90°C for 5–30 min (...) and during cooling from 90°C to 25°C (- - -).

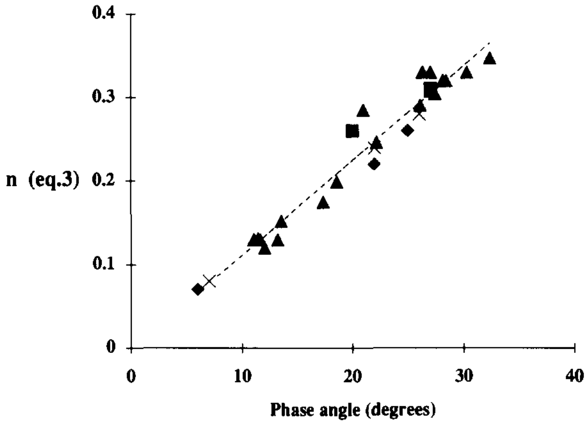

Fig. 7. Phase angles as a function of the slope value (n) in eqn (3) of pastes at the concentration of 5% (▲), 4% (■); 8% (×) and at 10% (◆).

angles and the slope values (n) for pastes at 5% concentration, a high correlation was achieved ($r = 0{\cdot}97$) ($n = 23$).

As expected from their dominantly elastic response implied by the low phase angles, low-sheared starch pastes (type I) were moderately frequency dependent and behaved like weak gels. According to Ross-

Murphy (1984) a weak gel is a reversible network system with an almost frequency independent shear modulus. The sheared pastes (type II) were more frequency dependent as can be seen in Fig. 6.

Phase-angle measurement

When determining the viscoelastic parameters during temperature gradients an interesting phenomenon was observed. The phase angle increased when the temperature was changing, but there was no detectable difference in the value of the complex modulus. The effect of rapid changes in temperatures on the phase angles is shown in Fig. 8. Changing the temperature during dynamic measurements of type I starch pastes induced an increase of phase angle values. The phase angle increased independent of whether the temperature was decreased or increased. After the change in temperature the phase angle returned to its original value.

The changes in phase angles were smaller when slower temperature gradients were used and differed between measuring geometries. The phenomenon was seen for low-sheared (type I) pastes during heating and cooling in the Rheometer. Since these changes in values of the phase angles cannot be neglected, the only values given in this report were those measured at constant temperatures. The reason for this effect needs to be further studied.

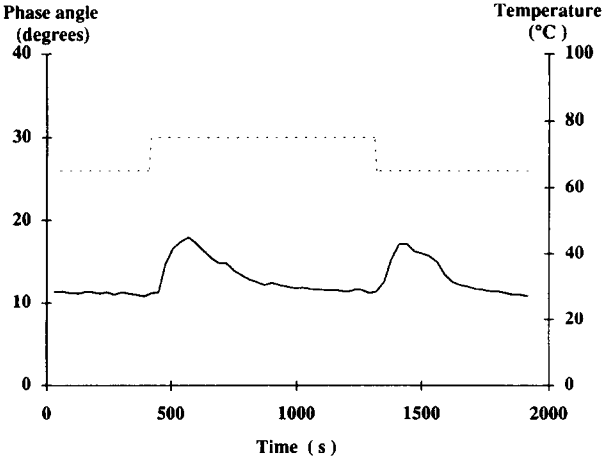

Fig. 8. Effect of changes in temperature during measurements on phase angles for a 5% paste transferred from the Brabender at 75°C. The set point temperatures are shown by the broken lines.

The effect of concentration

The transition between type I and type II behaviour is of prime importance for the concentration dependence.

The viscoelastic properties of starch pastes at different concentrations were studied using the same approach as that applied to low-sheared pastes. Pastes subjected to three different degrees of shear treatments were studied.

When sheared at a constant shear rate the shear forces are a function of the viscosity of the paste. In order to subject low-sheared pastes at different concentrations to similar shear history, the high concentration pastes were transferred when the 'Brabender viscosity' reached a fixed value (1200 BU) which was the Peak viscosity value of a 4% paste. The 4% and 5% pastes were transferred at Peak viscosity. Subsequently, the onset temperature for the dynamic measurements differed as follows: 4%, 73°C; 5%, 67°C; 8%, 61°C; 10%, 57°C.

The impact of the temperature on the complex modulus for the low-sheared pastes of different concentrations can be seen in Fig. 9 as continuous lines. The shapes of the complex moduli curves were almost independent of starch concentration in the range between 4 and 10%. The curves are similar to that of the low-sheared 5% paste previously discussed. At higher concentrations (8 and 80%) gelatinization was not completed when the dynamic measurements started. This explains the initial increase in the complex modulus.

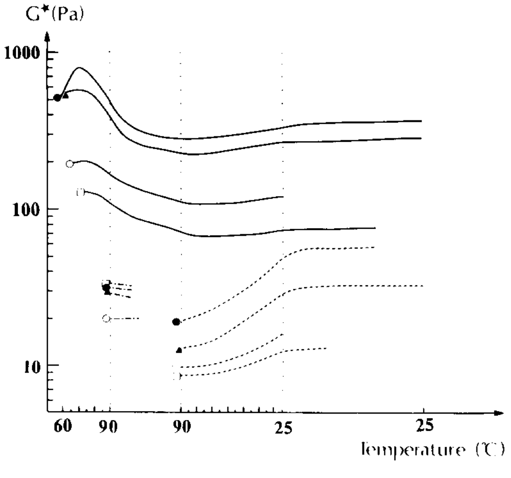

Fig. 9. Changes in the complex modulus at different concentrations. The low-sheared pastes are shown as continuous curves. Sheared pastes transferred at Hotpaste viscosity (90°C) at Breakdown viscosity (90°C, 30 min) are shown as broken lines. 10%; (●) 8%; (▲) 5%; (○) 4% (□).

The maximum values of the complex modulus for low-sheared pastes are depicted as a function of concentration in Fig. 10(a). The concentration dependence of the complex modulus was linear in this rather narrow concentration interval. A linear dependence for the shear modulus has previously been shown for potato starch pastes (Evans & Haisman, 1979). Even though there seems to be good agreement as regards the linearity of the shear modulus there are dissimilarities. Extrapolation of the linear plot and determination of the concentration (C_0) at zero modulus gives in our case a limit value of 2·3%. Evans and Haisman (1979) whose investigations were made under conditions comparable to the present study but in the concentration range 0·5–7% found this limit concentration to be $C_0 = 0{\cdot}23\%$. These differences in extrapolated limit concentrations (C_0) in fact indicate non-linear concentration dependence.

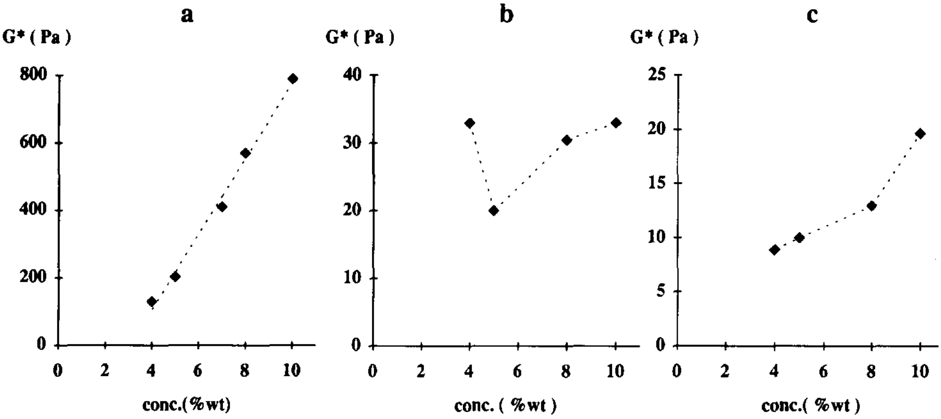

Fig. 10. The complex modulus against concentration for: (a) low-sheared pastes; (b) pastes at Hotpaste viscosity (90°C); (c) pastes at Breakdown viscosity (90°C, 30 min).

Changes in sheared pastes during the temperature treatment can be observed from the complex modulus curves of pastes sheared and heated to Hotpaste (90°C) and to Breakdown viscosity (90°C, 30 min) shown as broken lines in Fig. 9. The shear forces increase with the concentration in the Brabender viscograph because the viscosity increases with the concentration. The strong shear influence on potato starch pastes will cause anomalous concentration dependence in sheared pastes. At Hotpaste viscosity (90°C), the complex modulus is the same at 4% and at 10% starch. This can be seen in Fig. 9 and in Fig. 10(b). The low viscosity of the 4% paste protects it from shear-induced breakdown whilst the 10% starch was exposed to more extensive shear forces and probably had the low value of the complex modulus of type II consistency already at 90°C. The concentration dependence for sheared pastes was thus overpowered by the shear dependence in the samples heated and sheared to Hotpaste viscosity (90°C). When the shear modulus is plotted against the concentration, the result is a U-formed curve (Fig. 10(b)). This result gives no information about the concentration dependence but illustrates the importance of shear treatment.

At Breakdown viscosity it can be assumed that the pastes have reached type II behaviour. The non-linear character of the concentration dependence for these pastes transferred at Breakdown viscosity (90°C, 30 min) as shown in Fig. 10(c) are quite different from the linear concentration dependency of low-sheared (type I) pastes in the range 4–10% (see Fig. 10(a)). The sheared pastes also showed a stronger temperature dependence during cooling than did low-sheared pastes, as can be seen in Fig. 9. These differences in both concentration and temperature dependencies between type I and type II systems confirm the transformation between two types of viscoelastic behaviour. It can be expected that these types of starch pastes also differ in other matters, for example, the texture, the flow properties and the performance in industrial applications.

Interesting information was also given by the phase angles. At high temperatures the phase angles of the low-sheared pastes were almost independent of concentration in the range between 4 and 10% (Table 1), which is in agreement with results reported by Eliasson (1986). On the other hand phase angles varied with the concentration at low tempera-

TABLE 1
Phase Angles of Pastes Transferred at Different Stages in the Brabender Pasting Cycle at Different Concentrations (see Fig. 1)

Measurement temperature	*Concentration*			
	4%	*5%*	*8%*	*10%*
Low-sheared pastes				
90°C	12·5	11	10·5	10·5
25°C	13	11	7	6
Sheared pastes transferred at Hotpaste viscosity ($T = 90°C$)				
90°C	20	21	26	28
25°C	20	20	22	22
Sheared pastes transferred at Breakdown viscosity (90°C, 30 min)				
90°C	30	32	32	32
25°C	27	27	26	25

tures ($T=25$°C) as can be seen in Table 1. The phase angles decreased during cooling for pastes of 8 and 10% (Table 1). When the pastes were kept stored for another hour at 25°C there was a decrease in the phase angle at 8% and 10% and the complex modulus increased slightly. This implies a change in structure of concentrated low-sheared pastes during cooling. Storing at 25°C for 1 h had minor effects and further studies are needed in order to investigate the effect of longer storage times. In other investigations on potato starch systems the rheological behaviour has been found to change between the concentration of 5 and 8% at room temperature (Ring, 1985; Bohlin *et al.*, 1986).

During shearing in the Brabender the phase angle increased until it reached a plateau value at 30° as depicted in Fig. 3. This plateau value was valid at all concentrations (Table 1). Starch pastes at Breakdown viscosity (90°C, 30 min) all had phase angle values between 30 and 32° independent of concentration.

The phase angle of the pastes transferred at Hotpaste viscosity (90°C) reflected the extent of shear treatment. The 4% paste was the least sheared because of its lower viscosity and therefore had the lowest phase angles at 90°C (Table 1).

The co-variation between the degree of frequency dependence and the phase angles was common for all concentrations studied. This is shown in Fig. 7. The correlation coefficient between the slope value (n) of eqn (3) and the phase angle was 0·97 ($n=31$) for all pastes in this study. Since no further information is given by the frequency dependence, this only confirms the results given by the phase angle.

CONCLUSIONS

Shear is by far the most important factor for the viscoelastic characteristics of native potato starch dispersions when comparing with changes caused by heating after gelatinization. Two types of viscoelastic behaviour were found and the transition from one type to the other was determined by the amount of shear the sample had been subjected to. The transition took place early during the preparation in a Brabender viscograph.

Due to different shear forces generated at different concentrations, an anomalous concentration dependence can be obtained. In this study a negative concentration dependence was observed within a certain concentration range of sheared samples. Thus effects of shear needs to be taken into account when optimizing processing conditions, e.g. in scaling up operations.

ACKNOWLEDGEMENTS

The authors would like to thank their colleagues at Stärkelsen for financial support and encouragement throughout this work.

REFERENCES

Bohlin, L., Eliasson, A.-C. & Mita, T. (1986). *Stärke*, **38** (4), 120–4.

Doublier, J.-L. (1981). *Starch/Stärke*, **33** (12), 415–20.

Doublier, J. L., Llamas, G. & Le Meur, M. (1987). *Carbohydr. Polym.*, **7**, 251–75.

Donovan, J. W. (1979). *Biopolymers*, **18**, 263–75.

Egelandsdal, B., Fretheim, K. & Harbitz, O. (1986). *J. Sci. Food Agric.*, **37**, 944–54.

Eliasson, A.-C. (1986). *J. Text. Stud.*, **17**, 253–65.

Evans, I. D. & Haisman, D. R. (1979). *J. Text. Stud.*, **10**, 347–70.

Härröd, M. (1989). *J. Food Proc. Engng*, **11** (9), 257–75.

Hofstee, J. von (1962). *Starch/Stärke*, **9**, 318–24.

Launay, B., Doublier, J. L. & Cuvelier, G. (1986). In *Functional Properties of Food Macromolecules*, ed. J. R. Mitchell and D. A. Ledward, Elsevier Applied Science Publishers, London, pp. 1–78.

Muhrbeck, P. & Eliasson, A.-C. (1987). *Carbohydr. Polym.*, **7**, 291–300.

Osman, E. M. (1967). In *Starch: Chemistry and Technology, Vol. II*, ed. R. L. Whistler & E. F. Paschall. Academic Press, New York and London, pp. 163–210.

Ring, S. G. (1985). *Starch/Stärke*, **37** (3), 80–3.

Ross-Murphy, S. B. (1984). In *Biophysical Methods in Food Research*, ed. H. W.-S. Chan. Blackwell, pp. 138–99.

Schoch, T. J. (1965). *The Baker's Digest*, **39** (2), 48–57.

Wong, R. B. K. & Lelievre, J. (1981). *Rheol. Acta*, **20** (3), 299–307.

Wong, R. B. K. & Lelievre, J. (1982). *J. Appl. Polym., Sci.*, **27**, 1433–40.

Zobel, H. F. (1984). In *Starch: Chemistry and Technology*, ed. R. L. Whistler, J. N. BeMiller & E. F. Paschall. Academic Press, New York, pp. 285–305.