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Rheological behaviour of sago (*Metroxylon sagu*) starch paste

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Abstract

Rheological behaviour of gelatinized sago starch solution was studied over the shear rate range of 13.61–704 s^{-1} at various concentration and temperature ranges. A power law equation was used to describe the rheological behaviour of the starch solution, while the effect of temperature was evaluated by the Arrhenius equation. The effect of starch concentration on apparent viscosity was studied using the exponential model describing the relationship between apparent viscosity and concentration. Consistency index (κ) increased with concentration and decreased with the increase of temperature. Flow behaviour indices (η) were within the range of 0.495–0.559 which indicated the pseudoplastic nature of gelatinized sago starch. The amount of starch and shear rate affect activation energy (ΔE). Depending on the shear rate and concentration, activation energy varied from 0.619 to 1.756 kcal mol^{-1}. A mathematical relationship correlating the various parameters (temperature, concentrations, shear rates) was tested for its significance and validity. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Starch displays unique properties on heating with water. It exhibits unique viscosity behaviour with change of temperature, concentration and shear rate. The pseudoplastic property of gelatinized starch is important in many foods as it contributes to suspending properties at lower shear without rendering the food too viscous upon mixing or pouring at higher rates of shear. Flow behaviour characteristics can be estimated from the apparent viscosity and shear rate relationship. A number of researchers have worked on the flow properties of various hydrocolloids and food dispersions. Szczesniak (1986) and Szczesniak and Farkas (1962) related the flow properties to mouthfeel characteristics of food material. Whitcomb, Ek, and Macosko (1977) have used the power law model to characterise the flow behaviour of xanthan gum solution which relates the apparent viscosity to shear rate. The power law model is also widely used to describe the flow behaviour characteristics of many food systems such as tomato products, citrus juices, soups and sauces (Holdsworth, 1977). Apart from the rate of shear, substrate concentration, temperature and added salts may also influence the solution properties. Variation in apparent viscosity, due to changes in solid concentration and temperature, was also reported by Harper and El Sahrigi (1965). In a review by Holdsworth (1977) it was reported that the apparent viscosity relationship could be characterized by an Arrhenius model which linearly relates the logarithm of apparent viscosity (at a given shear rate) to the inverse of the absolute temperature. Various authors have correlated the effect of concentration or total solids with the viscosity and or with consistency index, when the fluid is non-Newtonian and follows the power law equation. However, Rao, Cooley, and Vitali (1984) and Ibarz, Vicente, and Graell (1987) have found that a number of fluids show better correlation between concentration and viscosity when evaluated by the exponential type of relationship. Exponential models expressed as $\kappa = Ae^{BC}$ (where A and B are constants) were used to evaluate the effects of concentration in some gums and hydrocolloids (Rao & Kenny, 1975), juice concentrates (Rao, Bourne, & Cooley, 1981; Rao, 1982; Vitali & Rao, 1982), egg products (Ibarz & Sintes, 1989), cow's milk and soy milk (Oguntunde & Akintoye, 1991), peach juice (Ibarz, Gonzalez, Esplugas, & Vicente, 1992a) and blackcurrant juice (Ibarz, Pagan, & Miguelsanz, 1992b). In the present study, the effect of various parameters,

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i.e. concentration, shear rates and temperatures, on the apparent viscosity of sago starch were evaluated by using the power law equation, exponential model and Arrhenius equation and a combination of all the effects in the form of a mathematical expression which may be used as a guideline for estimating the rheological behaviour of sago starch-formulated foodstuffs.

2. Materials and methods

Sago starch was obtained from a sago factory in Sarawak, Malaysia. The dry starch was dispersed in deionized distilled water in the amount of 3.0–5.5 g per 100 ml water. The starch dispersion was heated at 100°C to gelatinize the starch with constant stirring to avoid sedimentation and/or agglomeration. The gelatinized starch was then autoclaved at 125°C for 30 min to completely solubilize it. The solution was then filtered through glass wool to avoid the undissolved fraction of starch. The viscosity of the filtrate was then evaluated using a rotational viscometer (Contraves Rheomat 115). Apparent viscosity and shear stress were calculated from the read out torque at different levels of temperatures and concentrations at a varying rate of shear (13.64–704 s^{-1}). The flow behaviour index (η) and consistency coefficient (κ) were then calculated by fitting the viscometric data of power law equation, expressed as:

$$\tau = \kappa \gamma^{\eta} \qquad (1)$$

At each temperature, the effects of concentration (C) on the apparent viscosity at several shear rates were examined by fitting to the following equation:

$$\kappa = Ae^{BC} \qquad (2)$$

The parameters A and B were calculated as the intercept and slope of the plot of logarithm of apparent viscosity against logarithm of starch concentration. The variation in apparent viscosity due to temperature at each concentration was evaluated by using the Arrhenius model:

$$\kappa = Ae^{(\Delta E/RT)} \qquad (3)$$

where A is frequency factor, e is the natural logarithm base, ΔE is the activation energy and R is the gas constant, and T is the absolute temperature. The slope and intercepts of the regression of the plot of apparent viscosity against inverse of the absolute temperature were used to calculate the frequency factors and activation energies at each concentration. The combined relationship of apparent viscosity to shear rate, starch concentration and temperature were evaluated using multiple linear regression techniques. The logarithm of apparent viscosity was correlated with the logarithm of shear rate, logarithm of starch concentration and the inverse of the absolute temperature.

3. Results and discussion

The flow behaviour characteristic is influenced by the starch concentration and temperature. The consistency coefficients and flow behaviour indices for each temperature along with correlation coefficients for each flow curve are shown in Table 1. The consistency coefficients decreased with increasing temperatures at each level of concentration. The flow behaviour index increased with the increase of temperature at lower levels of concentration. However, it was not consistent at higher concentration and above 60°C, the trend was somewhat reversed. The consistency coefficient increased with increase of starch concentration but the flow behaviour index did not show a good trend with starch concentration. The value of η is always less than unity and

Table 1
Consistency coefficients and flow behaviour indices of sago starch dispersions at various temperatures and concentrations estimated by a power law equation in the form of $\tau = \kappa\gamma^{\eta}$

Temperature (°C)	Starch (g/100 ml)	κ (m Pa s^n)	η	r
40	3.0	6.008	0.529	0.992
	3.5	6.274	0.515	0.991
	4.0	6.502	0.517	0.994
	4.5	6.685	0.517	0.994
	5.0	7.203	0.524	0.996
	5.5	7.427	0.524	0.997
50	3.0	5.873	0.537	0.995
	3.5	6.149	0.523	0.994
	4.0	6.329	0.528	0.995
	4.5	6.521	0.528	0.995
	5.0	6.990	0.522	0.999
	5.5	7.186	0.521	0.999
60	3.0	5.719	0.547	0.997
	3.5	6.007	0.532	0.997
	4.0	6.154	0.536	0.996
	4.5	6.330	0.540	0.994
	5.0	6.709	0.519	0.994
	5.5	6.983	0.498	0.997
70	3.0	5.626	0.553	0.997
	3.5	5.973	0.526	0.996
	4.0	6.138	0.527	0.995
	4.5	6.319	0.526	0.996
	5.0	6.578	0.521	0.996
	5.5	6.792	0.511	0.997
80	3.0	5.523	0.559	0.995
	3.5	5.925	0.521	0.994
	4.0	6.090	0.521	0.991
	4.5	6.242	0.523	0.993
	5.0	6.428	0.523	0.996
	5.5	6.555	0.528	0.994

remains within the value of 0.498–0.559. It indicates that the starch solution is pseudoplastic and its pseudoplasticity decreases with temperature at each concentration and remains unaffected within the range of starch concentration used (3.0–5.5 g starch per 100 ml water), as evidenced by the fluctuating values of η. A plot of apparent viscosity against logarithm of shear rate over a wide range of shear (13.61–704 s^{-1}) showed that the viscosity decreases with the increase of shear rate at all levels of concentration at 40°C (Fig. 1). This suggests that the starch dispersion is susceptible to shear-thinning or pseudoplastic behaviour. Higher starch concentrations also resulted in higher apparent viscosity (at 117.1 s^{-1}) at each of the five temperatures. A significant correlation between logarithm of apparent viscosity and logarithm of starch concentration was observed at each temperature. However, the apparent viscosity decreased with increase of temperature, as evidenced by the decrease of consistency coefficient at each concentration. The apparent viscosity values were examined with respect to temperatures and it was observed that apparent viscosity decreased with increasing temperature. Upon fitting the data into an Arrhenius model a significant relationship was found at all levels of concentration. The activation energies, frequency factors and coefficients of determination are shown in Table 2. The activation energies and frequency factors varied at different shear rates. Effects of temperature at all shear rates were also observed. The magnitude of the effect varies with the starch concentration as evidenced by the values of the activation energies (Table 2). In general, the higher the activation energy the greater the effect of temperature on the viscosity. The frequency factor did not show any definite trend. The effect of temperature on viscosity is higher at higher concentrations as evidenced by the higher slope showed by the higher concentration line (Fig. 2). The effect of concentration was evaluated from the the plot of starch concentration against apparent viscosity at different temperature and is shown in Fig. 3. At each temperature level, apparent viscosity increased with increase of starch concentration. The relationship of apparent viscosity with the concentration was estimated from the exponential equation (Eq. (2)). The values of A and B in this equation were calculated by the least squares method and are shown in Table 2. The calculated values of A and B are significant at a probability level of $p < 0.05$. The values of B decrease with increase of temperature at a shear rate of 13.61 and 704 s^{-1}; however, the values of B do not show any particular trend with respect to temperature variation at other shear rates. The relationship of apparent viscosity to shear rate, starch concentration and temperature were combined in an equation similar to that used by Harper and El Sahrigi (1965). Using multiple regression the relationship obtained is:

$$\eta = 19.95.Y^{-1.01}.C^{1.5}.e^{-1.1T} \tag{4}$$

where the unit of apparent viscosity is m Pa s, C is the concentration of starch in g per 100 ml water and T is

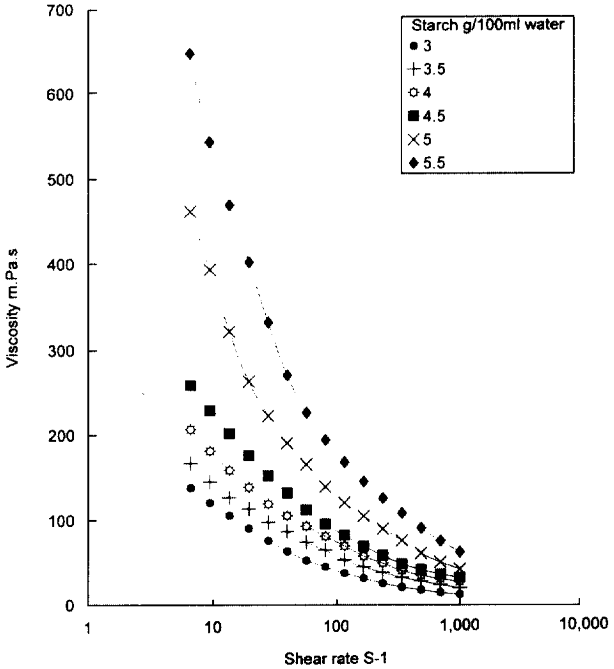

Fig. 1. Effect of shear rate on apparent viscosity at 40°C for 3.0–5.05 g starch in 100 ml dispersion.

Table 2
Apparent viscosity as a function of temperature for sago starch dispersions at different concentrations ranging from 3.0 to 5.5 g per 100 ml water based on the Arrhenius equation $\kappa = Ae^{\Delta E/RT}$

Shear rate (s^{-1})		Concentration (g per 100 ml water)					
		3.0	3.5	4.0	4.5	5.0	5.5
13.61	A[a]	1.712	2.847	1.853	2.014	1.335	0.256
	Ea[b]	0.915	0.619	1.009	1.011	1.321	1.756
	r[c]	0.988	0.993	0.935	0.988	0.999	0.979
13.61	A	0.594	0.310	0.232	0.931	0.774	0.386
	Ea	1.123	1.289	1.376	1.217	1.339	1.535
	r	0.998	0.990	0.989	0.992	0.977	0.990
117.1	A	1.133	0.207	0.235	0.405	0.688	1.080
	Ea	1.216	1.234	1.294	1.289	1.236	1.167
	r	0.998	0.974	0.999	0.984	0.998	0.999
240	A	0.987	0.979	0.429	0.796	1.026	0.643
	Ea	0.772	0.814	1.066	1.012	1.032	1.176
	r	0.992	0.998	0.996	0.986	0.985	0.995
704	A	0.413	0.513	0.413	0.548	0.398	0.194
	Ea	0.753	0.794	0.908	0.931	1.034	1.171
	r	0.997	0.983	0.995	0.997	0.999	0.989

[a] m Pa s^n.

[b] kcal mol^{-1}.

[c] Regression coefficient.

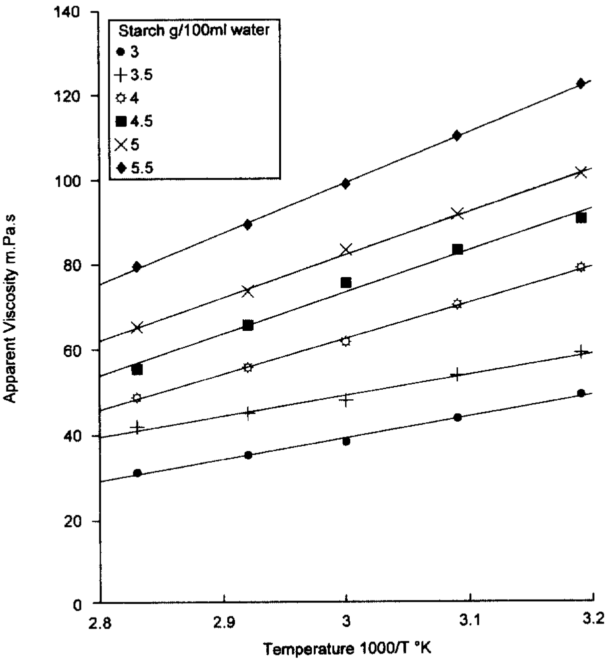

Fig. 2. Apparent viscosity (at 117.1 s^{-1}) as a function of temperature for sago starch dispersion at concentrations of 3.0–5.5 g starch per ml water.

the temperature in K. The equation fits the data as indicated by the coefficient of multiple regression determination of 0.969 with a standard deviation of 0.062 for the 252 data points.

The decrease of apparent viscosity with the increase of shear rate suggests that the increasing shear rate progressively disentangles the arrangements of long chain molecules and helps to overcome the intermolecular resistance to flow. On the other hand, the highly solvated molecules or particles present in the dispersion medium may be progressively sheared away with increasing shear rate causing a reduction in the effective size of the particles and hence a reduction in apparent viscosity (Holdsworth, 1977).

The viscosity of a liquid is a function of the intermolecular forces that restrict molecular motion. These forces depend on the intermolecular spacings which determine the free volume and are affected by changes in both temperature and pressure. Consistency is a function of viscosity. On heating at a constant pressure, the thermal energy of the molecule increases with the increase of intermolecular distances, causing reduction of intermolecular forces and consequently, at higher temperature, the viscosity decreases (Holdsworth, 1977).

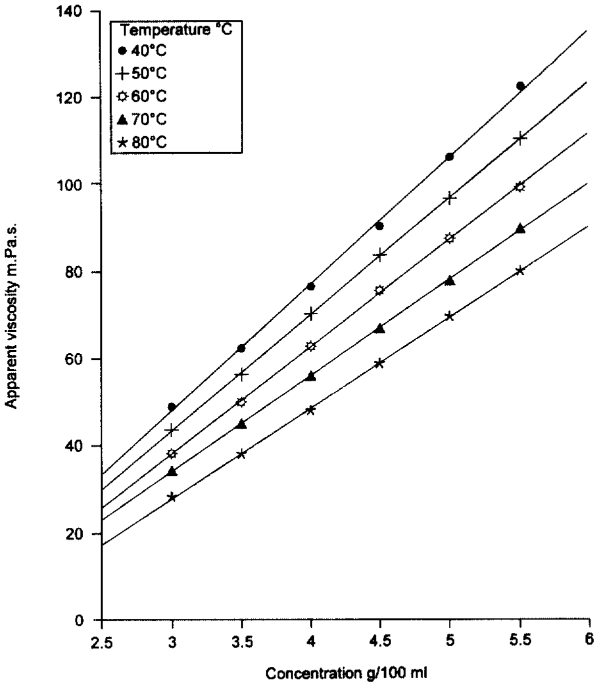

Fig. 3. Concentration vs apparent viscosity (at 117.1 s^{-1}) of sago starch.

Table 3
Apparent viscosity as a function of concentration for sago starch dispersions from 40–80°C at different shear rates using the exponential model of type $K = Ae^{BC}$

Shear rate (s^{-1})		Temperature (°C)				
		40	50	60	70	80
13.61	A[a]	3.233	3.148	3.060	3.211	3.410
	B[b]	0.464	0.459	0.450	0.396	0.328
	r[c]	0.996	0.996	0.992	0.996	0.997
57.2	A	2.961	2.747	2.687	2.666	2.662
	B	0.413	0.441	0.425	0.402	0.373
	r	0.997	0.999	0.998	0.999	0.998
117.1	A	2.831	2.709	2.551	2.529	2.451
	B	0.363	0.367	0.378	0.360	0.350
	r	0.991	0.991	0.991	0.993	0.992
240	A	2.198	2.140	2.040	2.053	2.096
	B	0.405	0.402	0.403	0.380	0.346
	r	0.993	0.992	0.991	0.987	0.987
704	A	1.336	1.479	1.450	1.433	1.444
	B	0.489	0.429	0.417	0.401	0.376
	r	0.993	0.998	0.997	0.998	0.997

[a] m Pa s^n.
[b] Slope of the regression line.
[c] Regression coefficient.

4. Conclusions

Sago starch solution exhibits shear-thinning (pseudoplastic) behaviour. The pseudoplasticity varies with temperature as evidenced by increased η values at higher temperatures but the pseudoplasticity remains unaffected within starch concentration ranges of 3.0–5.5 g starch per 100 ml water. Shear rate, starch concentration and temperature influence rheological properties.

Hence, the apparent viscosity could be related to shear rate, temperature and starch concentration by a single expression using the multiple regression equation in the form of $\eta = \kappa . \gamma^{A} . C^{B} . e^{\Delta E/RT}$ (η = viscosity, κ, A, B are constants; γ = shear rate, C = concentration, e = natural logarithm, ΔE = activation energy, R = gas constant and T = K temperature). This equation could be used in food product research and development. A desirable viscosity could be obtained at a fixed shear rate or concentration and/or temperature by varying the other two parameters. However, this approach may provide a first estimate of the amount of starch needed and should reduce the time spent in achieving the desired textural properties for a product.

Acknowledgements

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