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The thixotropic and rheopectic behaviour of maize starch and maltodextrin thickeners used in dysphagia therapy

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Abstract

The viscosity of starch-thickened foods is critical in managing dysphagia (impaired swallowing). These fluids are highly non-Newtonian and exhibit thixotropic behaviour. The thixotropy of the starch-based thickeners that are used to achieve this critical viscosity is presented. Two types of thickeners were evaluated; maize-based and maltodextrin-based. The thixotropy of these thickeners proved to be complex and the behaviour could be toggled between thixotropy and rheopexy by changing certain variables. The sol to gel transition favours low or zero shear rates when the initial viscosity is low (low starch concentration), but shearing is preferred for structure formation of high viscosity (concentrated) samples. This is likely to be due to Brownian motion being restricted in thicker samples due to less solvent between starch molecules. This may also cause starch granules to be sheared open causing more amylose to enter the viscous matrix.

Keywords: Viscosity; Thixotropy; Rheopexy; Starch; Maize; Maltodextrin; Thickeners; Dysphagia

1. Introduction

The characterisation of time-dependent rheological properties of foods is important in establishing storage and handling protocols. The characterisation of the thixotropy of the starch-thickened foods used for dysphagia therapy is critical and to the best of our knowledge has not collectively been reported.

This work examines the thixotropy of two general classes of starch-based thickener. The two classes are maize starch and maltodextrin in the presence of a non-ionic polysaccharide (carob bean gum). Maltodextrins are produced by the enzymatic degradation of starch. It is widely known within the food industry that non-starch hydrocolloids, such as carob bean gum, exhibit many functions to control rheological and textural properties of foods and help to maintain overall product quality during storage (Glicksman, 1969). The addition of non-starch hydrocolloids has been shown to enhance the gelatinization and retrogradation behavior of starch (Alloncle & Doublier, 1991; Christianson, Hodge, Osborne, & Detroy, 1981; Funami et al., 2005; Sajjan & Rao, 1987; Yoshimura, Takaya, & Nishinari, 1996).

This paper investigates the viscosity of these two thickeners during constant shear over several hours and establishes a thixotropic (shear-time thinning) or rheopectic (shear-time thickening) response.

1.1. Background

Dysphagia is a common, but relatively short-lived sequelae of a cerebrovascular accident and can occur on a chronic basis as a result of many neuro-degenerative diseases. The condition occurs in as many as 60% of stroke patients (Mann, Hankey, & Cameron, 1999) and can lead to dehydration, malnutrition and most notably pulmonary aspiration (Axelsson, Asplund, Norberg, & Eriksson, 1989; Weinberg & Minaker, 1995). Aspiration aids the transport

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of pathogenic bacteria into the lungs and can lead to aspiration pneumonia (Langmore, Skarupski, Park, & Fries, 2002; Langmore et al., 1998). Numerous respiratory problems have been related to aspiration (Marik, 2001). Dysphagic stroke patients have difficulty swallowing fluids and often have their fluids thickened with a starch-based thickener as part of prescribed therapy. This increases the viscosity of the fluid.

It has been shown using an electromyography, manometry and videofluoroscopy techniques (Dantas et al., 1990; Ekberg, Liedberg, & Owall, 1986; Lazarus et al., 1983; Reimers-Neils, Logemann, & Larson, 1994) that fluids with increased viscosity have increased transit times during the swallow due to the increased oropharyngeal muscle activity. Higher viscosity fluids allow more time for the patient to trigger the swallowing reflex (Logemann, 1983).

It is vital that drinks of the correct viscosity are prepared consistently, as too low a viscosity may travel faster into the pharynx and may be more likely to enter the airway before protective mechanisms can be initiated. Too high a viscosity is rejected by patients and can lead to malnutrition and dehydration. In some patients a high viscosity and hence increased transit time increases the likelihood of aspiration. Miller and Watkin (1996) and Goulding and Bakheit (2000) illustrated that a high viscosity fluid can aggravate swallowing and may worsen dysphagia. Therefore it is clear that the viscosity must be precise to within a certain degree, as a low viscosity causes harm to health and a high viscosity is rejected and in some cases also causes harm.

Starch is the key ingredient in providing the desirable rheological characteristics of food products (Yang, Irudayaraj, Otgonchimeg, & Walsh, 2004) and is ideal as a thickening agent. Starch granules are semi-crystalline particles composed of a mixture of two polysaccharides, amylose and amylopectin. These two polysaccharides associate via hydrogen bonds either directly or through hydrate bridges, forming semi-crystalline micelles that exhibit birefringence and consequently yield amorphous areas (Christianson et al., 1981). These semi-crystalline regions are insoluble and are composed mainly of short chains of branched amylopectin arranged in a three-dimensional lattice through a double-helix formation (Zobel & Stephen, 1995). The amorphous regions are composed of amylose molecules in a single-stranded helix formation. These regions undergo water imbibition (Zobel & Stephen, 1995). Therefore, a starch gel can be regarded as a composite material, in which the continuous phase of the amylose gel matrix has swollen gelatinized granules made up of amylopectin distributed within it (Eliasson, 1986; Keetels, van Vliet, & Walstra, 1996). The rheological properties of the continuous phase, the deformability of the dispersed phase and the interactions between these two phases are associated with the mechanical properties of starch gels (Keetels et al., 1996).

Since starch gels undergo water imbibition and rely upon the formation of hydrogen bonds for structure, it is understandable that their rheology is extremely time-dependent. As mentioned, starch pastes and gels are composite materials whose rheological properties are determined by interactions between the swollen starch granules (dispersed phase) and the continuous viscous matrix (Carnali & Zhou, 1996; Doublier, Llamas, & Paton, 1987; Nguyen, Jensen, & Kristensen, 1998). The rheological time-dependent characterisation of starch foods establishes relationships between structure and flow. This allows correlation with sensory evaluation (Figoni & Shoemaker, 1983). Thixotropy is the most common form of time-dependent behaviour. When a thixotropic system is sheared at a constant rate, the apparent viscosity decreases with time until a balance between structural breakdown and re-formation is reached (Shaw, 1999). Given time, the sheared system usually regains its original structure unless it is rheomalaxic (irreversible shearing). A thixotropic hysteresis loop and a value for the thixotropy of a fluid can be obtained (the area of the loop) through experimentation. Although useful for demonstrating the fluid as being non-Newtonian, shear-thinning and thixotropic, the results can only be considered as qualitative because the hysteresis is affected by the shearing cycle time, shear history and maximum shear rate (Nguyen et al., 1998). The thixotropy of a fluid can be quantified by observing the decay curve and, consequently, the decay rate when the fluid is sheared at a constant rate over a set period.

The stress decay data can be used to model irreversible thixotropy by adding a structural decay parameter to the Herschel–Bulkley model (Tiu & Boger, 1974)

$$\tau = F(\lambda, \dot{\gamma}) = \lambda(\tau_0 + K(\dot{\gamma})^n), \tag{1}$$

where τ is shear stress, λ is the structural parameter and is a function of time, τ_0 is yield stress, K is the consistency coefficient, n is the flow behaviour index and $\dot{\gamma}$ is shear rate. λ can be determined by equating the definition of the apparent viscosity to Eq. (1) (Steffe, 1996), which gives the expression below:

$$\lambda = \frac{\eta\dot{\gamma}}{\tau_0 + K(\dot{\gamma})^n}. \tag{2}$$

Many models have been proposed to describe the time-dependent behaviour, which are well summarised by Holdsworth (1993) and Mujumdar et al. (2002). One of the earliest to be specifically applied to food was the Weltman model (Weltman, 1943) and, more recently, the structural kinetic model (SKM) has been successfully applied to starch pastes (Nguyen et al., 1998) and to semisolid foodstuffs (Abu-Jdayil, 2003). The pioneering work of Nguyen et al. (1998) illustrated that this model could be applied to starch fluids and the derivation is repeated here for clarity. The SKM uses an analogy with chemical equilibrium reactions as shown below:

$$(\text{Stuctured}) \rightarrow (\text{Non-structured}).$$

The structured state depends on the kinetics of this process and can be represented by a dimensionless structural parameter, Ψ, which is defined as

$$\Psi(t,\dot{\gamma}) = \frac{(\eta - \eta_\infty)}{(\eta_0 - \eta_\infty)}, \tag{3}$$

where η_0 is the initial apparent viscosity at $t = 0$ (structured state) and η_∞ is equilibrium apparent viscosity as $t \to \infty$ (non-structured state). The rate of structural breakdown can be expressed as

$$-\frac{d\Psi}{dt} = k(\Psi - \Psi_\infty)^n, \tag{4}$$

where $k = k(\dot{\gamma})$ is the rate constant and is an indication of the rate of thixotropic breakdown (Nguyen et al., 1998) The order of the structure breakdown process is given as n. This indicates whether the equilibrium reaction, which the SKM is based on is of zero, first, second or higher-order. Integration of Eq. (4) at a constant shear rate from $t = 0$ to t gives

$$(\Psi - \Psi_\infty)^{1-n} = (n-1)kt + (\Psi_0 - \Psi_\infty)^{1-n}. \tag{5}$$

Substituting Eq. (5) into Eq. (3) for a fixed shear rate yields the structural kinetic model

$$\left[\frac{(\eta - \eta_\infty)}{(\eta_0 - \eta_\infty)}\right]^{1-n} = (n-1)kt + 1. \tag{6}$$

This allows us to calculate the parameters n and k for a fixed shear rate. It has been shown that k generally increases with increasing shear rate (Abu-Jdayil, 2003; Nguyen et al., 1998). Application of the SKM to starch pastes illustrated a good fit for a third-order irreversible kinetic model ($n = 3$) (Nguyen et al., 1998).

The physical interpretation of thixotropy is often associated with the process of intermolecular attractions and entanglements becoming overcome and the extent of solvent immobilisation being reduced upon shearing. Brownian motion restores the solution to its original condition when little or no shearing occurs in recoverable fluids. The presence of thixotropy in starch-thickened fluids can be described in terms of a sol–gel transition phenomenon. Once produced, the fluid slowly develops a three-dimensional network, possibly through hydrogen bonding between adjacent hydroxyl groups, and may be described as a gel. When sheared, the structure is broken down and the material reaches a minimum viscosity where it exists in the sol state (Steffe, 1996). This can be considered as a suspension of swollen starch granules in a viscous solution (Nguyen et al., 1998).

Recent papers have addressed thixotropy within starch foodstuffs. Tarrega, Velez-Ruiz, and Costell (2005) indicated thixotropic or anti-thixotropic behaviour in milk and starch dispersions. Meng and Rao (2005) illustrated time-dependent behaviour in maize starch dispersions prepared in apple juice and water. Abu-Jdayil, Mohameed, and Eassa (2004) demonstrated that most starch–milk–sugar systems exhibit thixotropic behaviour although a 2% w/w permutation of wheat–milk–glucose was rheopectic. In addition, previous papers have highlighted that starch dispersions can exhibit both thixotropy and rheopexy (Carriere, 1998; Dintzis & Bagley, 1995; Doublier et al., 1987; Rao, Okechukwu, Da Silva, & Oliveira, 1997; Tattiyakul & Rao, 2000). These papers report the shear stress or shear rate at which starch dispersions' time-dependent response changes. The complex time-dependence of these dispersions is highlighted by the varied conflicting data within these papers. This paper reports that concentration and shear rate are important in whether maize starch dispersions exhibit thixotropy or rheopexy. We highlight the clinical significance of this in managing dysphagia and compare with maltodextrin-based thickeners which are a common alternative to maize-thickeners within dysphagia therapy.

2. Methods

2.1. Sample preparation

All experiments were performed on a Brookfield concentric cylinder R/S rheometer using a double-gap concentric cylinder attachment (unless stated otherwise) distributed by Carl Stuart Ltd., UK. The rheometer was programmed using Brookfield RHEO 2000 software via a networked PC. Temperature was controlled by a Lauda, Eco Line RE204 computer-controlled circulator at a constant 20.0 °C for all experiments. Two different brands of thickener were used. The maize-based starch is 99.2% maize starch, 0.4% sucrose, 0.3% glucose and 0.1% lactose. The maltodextrin is 64% maltodextrin, 35% carob bean gum and 1% calcium lactate. Each sample was made by adding 0.5, 1, 1.5, 2 or 2.5 g (±0.0005 g) of the corresponding commercial starch thickener to 50 ml (±0.08 ml) of ordinary tap water that had been filtered using a commercially available water filter. These are equivalent to 1, 2, 3, 4 and 5% w/v, respectively. De-ionised water was not used as this is not consistent with real life applications of the thickener. Throughout this paper, 'concentration' refers to the number of grams in 50 ml of water. All solutions were made by mixing the powdered starch into the water for 30 s at an approximate shear rate of 50 s^{-1} at room temperature (21–22 °C). The solutions were allowed to stand for 5 min before being stirred at a similar shear rate for 30 s. For the temporal viscosity experiments, the samples were placed in the rheometer and were left in the rheometer for 15 min prior to starting the experiment to allow structure formation.

2.2. Experimentation

One method of estimating thixotropy is by observing the hysteresis in the form of a thixotropic loop. The thixotropic loop of the fluid provides useful qualitative data and illustrates whether the solution undergoes rheomalaxis. The

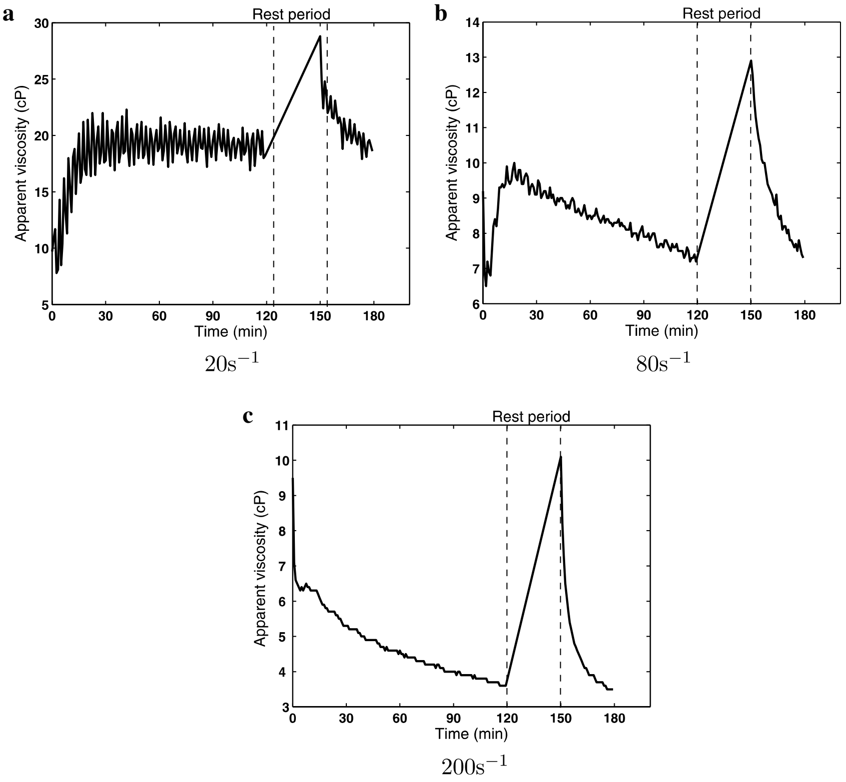


Fig. 1. Selection of maize-thickener thixotropy plots (time versus viscosity) for 0.5 g concentration, illustrating normal thixotropic behaviour. Samples are subjected to a constant shear rate (caption) at constant temperature of 20.0 °C. (a) 20 s^{-1}, (b) 80 s^{-1}, (c) 200 s^{-1}.

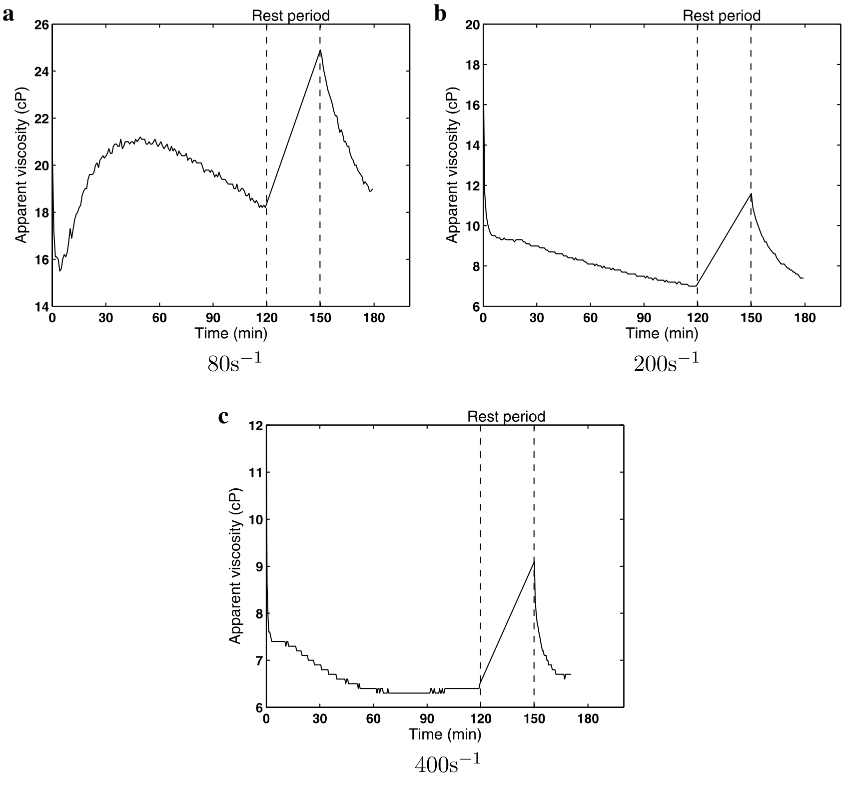
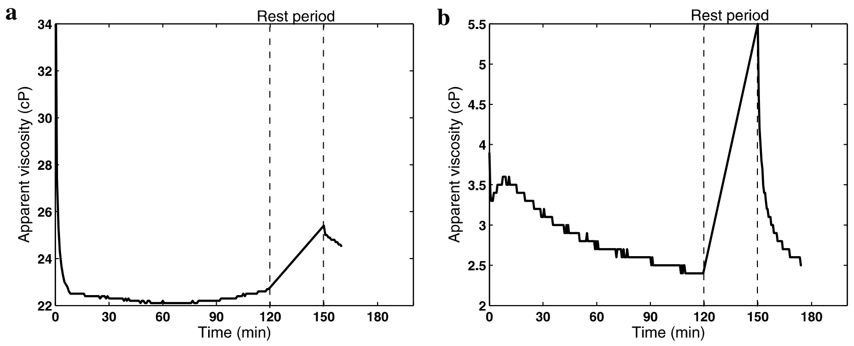


Fig. 2. Selection of maize-thickener thixotropy plots (time versus viscosity) for 1.0 g, illustrating normal thixotropic behaviour. Samples are subjected to a constant shear rate (caption) at constant temperature of 20.0 °C. (a) 80 s^{-1}, (b) 200 s^{-1}, (c) 400 s^{-1}.

measurement involves a rate ramp up to a peak shear rate, then a ramp down back to zero. Measuring thixotropy in this way is relative and all parameters must be kept constant when comparing different solutions (i.e., a fast rate ramp produces a larger thixotropic loop than a slower rate ramp). Consequently, a more quantitative measurement of thixotropy was used in this work. The sample is subjected to a constant shear rate for a specific amount of time. The experiments involved subjecting a variety of samples of different concentration to shear rates of 20, 80, 200 and 400 s^{-1}. A shear rate of 20 s^{-1} corresponds approximately to the shear subjected by gentle stirring and 80 s^{-1} to the shear subjected on the sample during the swallow (Sherman, 1988) (although this is most likely a high estimate as others have suggested it to be 50 s^{-1} (Wood, 1968) but results for 50 s^{-1} were observed to be very similar to 20 s^{-1}). Shear rates 200 and 400 s^{-1} were chosen as they represent more intensive stirring, i.e., a hand whisk. A rest interval of 30 min was allowed after the sample had been sheared for 2 h, at which point it was sheared for a further 30 min. This was done to investigate the possibility of any structural recovery of the sample.



$200s^{-1}$ $400s^{-1}$

Fig. 3. Selection of maize thixotropy plots (time versus viscosity) for 1.5 g, illustrating normal thixotropic behaviour. Samples are subjected to a constant shear rate at constant (caption) temperature of 20.0 °C. (a) 200 s^{-1}, (b) 400 s^{-1}.

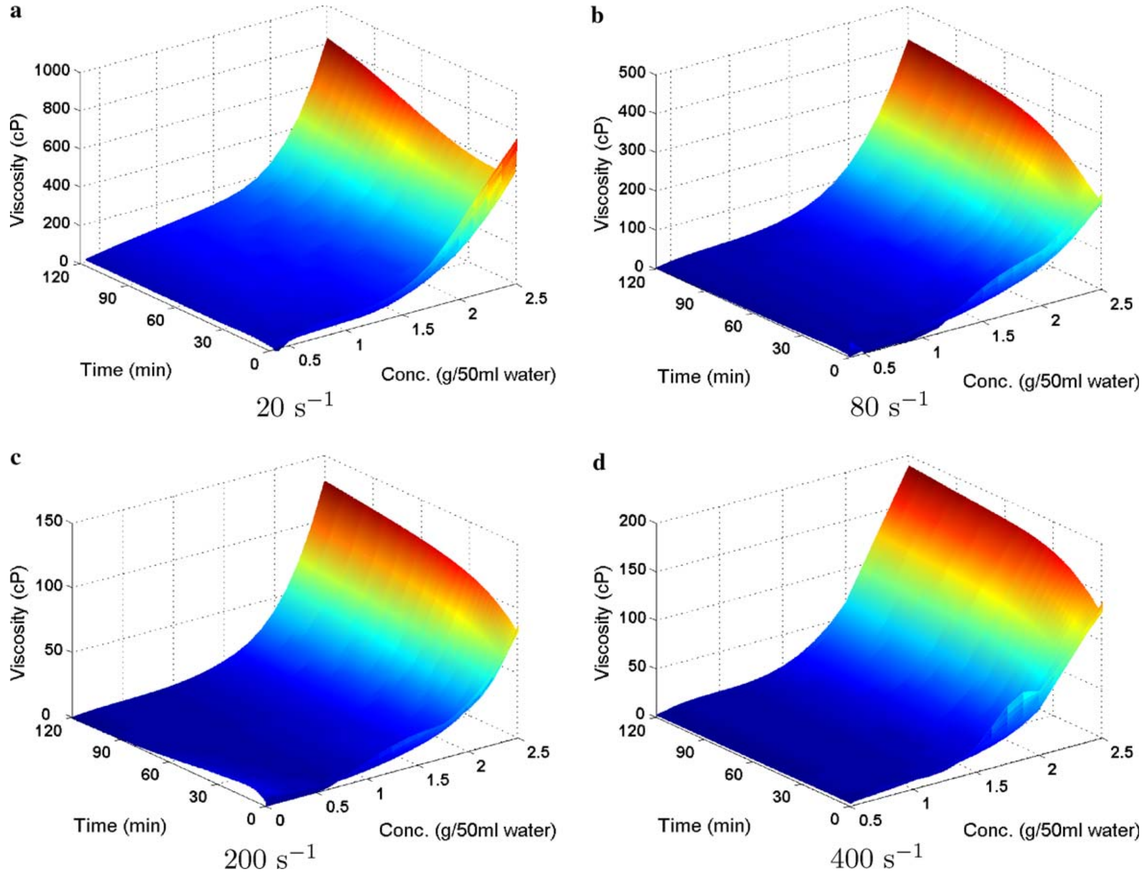


Fig. 4. Surface plots of thixotropy for varying concentration of maize-based thickener at four specific shear rates of 20, 80, 200 and 400 s^{-1}. The experiments were performed at a constant temperature of 20.0 °C. (a) 20 s^{-1}, (b) 80 s^{-1}, (c) 200 s^{-1}, (d) 400 s^{-1}.

Table 1
The degree and extent of thixotropy of maize starch samples, evaluated at different concentrations and fixed shear rates of 200 and 400 s^{-1}, using the structural kinetic model

Concentration	$k \times 10^3$	η_0/η_∞	χ_v^2
200 s^{-1}			
0.5	2.191	2.81	0.96
1.0	5.301	2.59	2.96
1.5	40.684	1.70	0.13
400 s^{-1}			
0.5	1.213	1.79	0.12
1.0	6.135	3.2	0.20

χ_v^2 for 3600 degrees of freedom and a common uncertainty of 0.5 cP is also given.

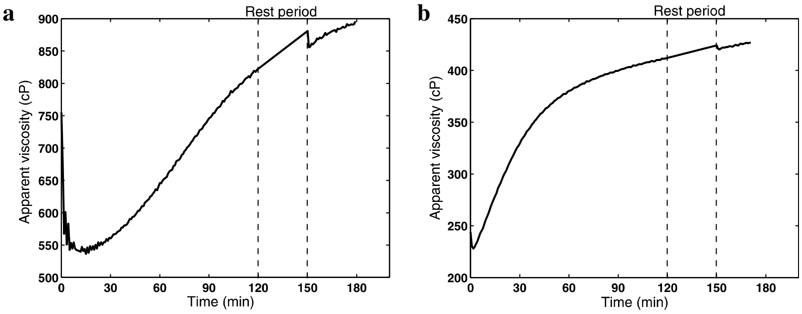
3. Results

3.1. Maize-based thickener

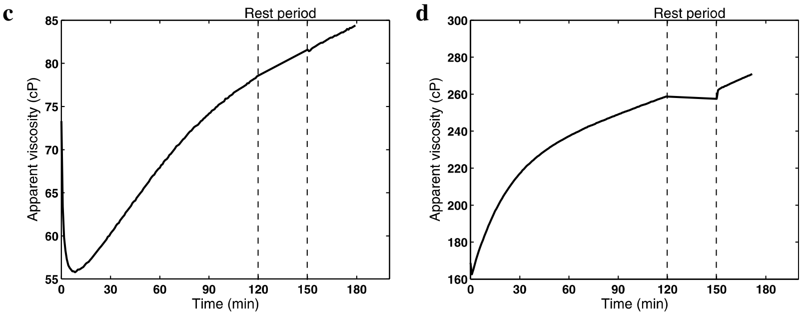
Figs. 1–3 are a selection of thixotropy plots for a maize-based thickener. These plots were chosen as they exhibit standard thixotropic behaviour. The remaining plots do not exhibit typical thixotropic behaviour and a selection are shown in Fig. 5. Fig. 4 shows all the thixotropy data in four surface plots. Table 1 shows the parameters for the structural kinetic model which facilitates in quantifying thixotropy.

3.2. Maltodextrin-based thickener

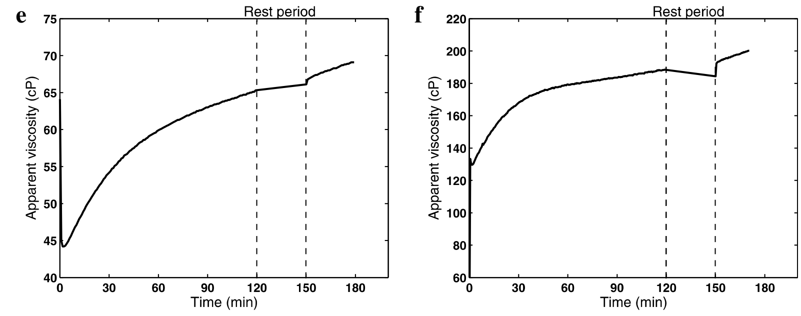
Unlike the maize-based thickener the maltodextrin-based thickener exhibits no thixotropic behaviour for any



2.5g at $20s^{-1}$ 2.5g at $80s^{-1}$



2.0g at $200s^{-1}$ 2.5g at $200s^{-1}$



2.0g at $400s^{-1}$ 2.5g at $400s^{-1}$

Fig. 5. Selection of maize-thickener thixotropy plots (time versus viscosity) illustrating rheopectic behaviour. Samples are subjected to a constant shear rate at constant temperature of 20.0 °C. (a) 2.5 g at 20 s^{-1}, (b) 2.5 g at 80 s^{-1}, (c) 2.0 g at 200 s^{-1}, (d) 2.5 g at 200 s^{-1}, (e) 2.0 g at 400 s^{-1}, (f) 2.5 g at 400 s^{-1}.

permutation of shear rate and concentration. The general behaviour can be classed as rheopectic. Figs. 6 and 7 are a small selection as all the data behaved in a similar manner.

4. Discussion

4.1. Maize-based thickener

Figs. 1–5 are plots of viscosity versus time for maize when the sample is sheared at a constant rate. The trends appear to be significantly dependent on concentration and shear rate. Figs. 1–3 are plots which exhibit some thixotropy, whereas the data in Fig. 5 exhibit no thixotropy and are better characterised by rheopexy.

Figs. 1–3 present all the plots which showed any thixotropy. The remaining plots were similar to those shown in Fig. 5. Since all the samples which show any thixotropy are of a low concentration, Figs. 1–3 indicate that for these low concentrated samples (low viscosity), increasing the shear rate prevents the colloid from building a network and responds to the shear in a more thixotropic manner. This seems to be overcome by increasing the concentration, i.e., structural network formation is favoured with lower shear rates and higher starch concentrations (high viscosity). Table 1 illustrates the degree of thixotropy for the samples at 200 and 400 s^{-1} by using the structural kinetic model for a second-order reaction ($n = 2$). A second-order reaction provided the best fit to the data unlike the work of Nguyen et al. (1998) and Abu-Jdayil (2003), where a third-order reaction was used. In agreement with Nguyen et al. (1998) and Abu-Jdayil (2003), k increases with shear rate. This model could not be fitted to all data.

Fig. 5 and the data in Table 2 suggest that as the concentration of starch Table 3 increases, a certain amount of shearing is preferred to build a structured network. Figs. 5a–c illustrate that the recovered viscosity is no different to what it would be, by extrapolation, if shearing continued. This suggests that small amounts of shear within highly concentrated maize-thickened fluids has no effect on the viscosity change over time. As the amount of shear and starch concentration increases, the recovery period becomes adverse to structure formation. Figs. 5d–f and the latter data in Table 2 indicate that shearing for high concentrations is favourable for structure formation. The figures indicate network formation between the amylose and amylopectin molecules (increasing viscosity) during shearing and structural breakdown during the rest period, since the recovery is negative and the trend is rheopectic after the recovery period. The plots shown in Figs. 1–3 and the data in Table 2 show that the reverse is true for fluids of a low concentration.

Generally, shearing thicker maize samples causes an increase in viscosity over 2 h. In our previous studies, allowing a similar sample to rest also causes the viscosity to increase whereas lower viscosity maize samples initially decrease in viscosity when at rest (Dewar & Joyce, in press).

Table 2
The degree of recovery of maize starch samples, evaluated at different concentrations and fixed shear rates of 20, 80, 200 and 400 s^{-1}

$\dot{\gamma}$	Concentration	η_{120}	η_{150}	Recovery ($\eta_{150} - \eta_{120}$)	Relative recovery % ($\frac{\eta_{150}-\eta_{120}}{\eta_{120}} \times 100$)
20 s^{-1}	0.5	19	28.8	9.8	51.6
	1.0	70.2	87.8	17.6	25.1
	1.5	115	137.6	22.6	19.7
	2.0	248.9	269.2	20.3	8.2
	2.5	810.3	871.3	61.0	7.5
80 s^{-1}	0.5	7.5	12.9	5.4	72.0
	1.0	18.2	24.9	6.7	36.8
	1.5	39.5	47.8	8.3	21.0
	2.0	132.1	139.9	7.8	5.9
	2.5	413.0	424.2	11.2	2.7
200 s^{-1}	0.5	3.7	10.1	6.4	173.9
	1.0	6.9	11.6	4.7	68.1
	1.5	22.7	25.4	2.7	11.9
	2.0	78.5	81.6	3.1	3.9
	2.5	259.0	257.5	−1.5	−0.6
400 s^{-1}	0.5	2.4	5.5	3.1	129.1
	1.0	6.4	9.1	2.7	42.2
	1.5	17.3	18.3	1.0	5.8
	2.0	65.3	66.1	0.8	1.2
	2.5[a]	188.5	184.3	−4.2	−2.2

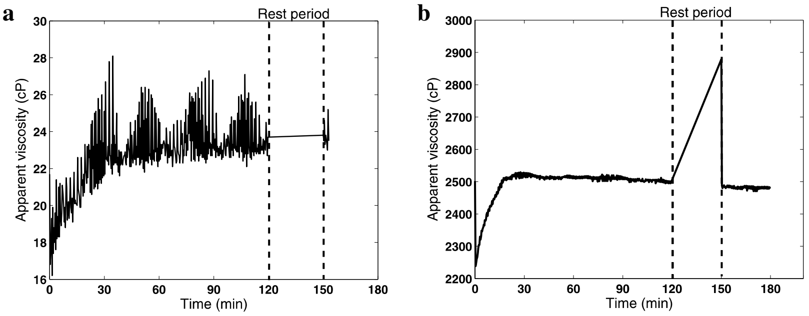
Subscripts on η refer to viscosity at that time in minutes. All viscosity values are in cP.

[a] Double gap torque exceeded. CC25 attachment used.

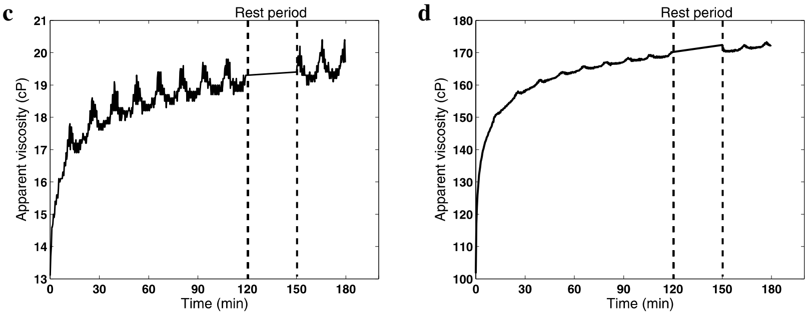
Table 3
Viscosity boundaries experimentally defined for dysphagia therapy by Smith et al. (1997)

Consistency term	Sub-category	Viscosity (cP)
Thick	High	2240+
	Low	577+
Medium	High	202+
	Middle	82+
	Low	30+
Thin	High	9.5+
	Low	3+

The relative recovery values show that low starch concentrations prefer little or zero shear to form a gel structure, and the figures illustrate these large amounts of recovery during the rest period. These results can be explained by the gel being considered as a composite material undergoing simple Brownian motion (Steffe, 1996). The less concentrated samples have large amounts of solvent and fewer starch molecules. The amylose molecules are free to move randomly in the solvent and form hydrogen bonds with other molecules forming a weak matrix. The amylopectin molecules form sparse aggregates of insoluble micelles. Shearing causes turbulence in the solvent which is enough to push the equilibrium between non-structured and structured further to the non-structured and lower the viscosity of the continuous phase. Therefore the viscosity of the fluid decreases with shearing. The more concentrated samples are more densely packed with less solvent available between each molecule. Movement is restricted and Brownian motion allows only some bonds to be formed. Shearing the sample allows the molecules to make more collisions and more permutations of molec-

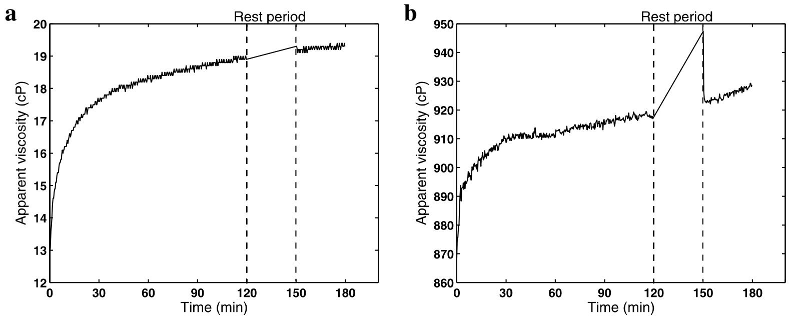


0.5g at $20s^{-1}$ 2.0g at $20s^{-1}$

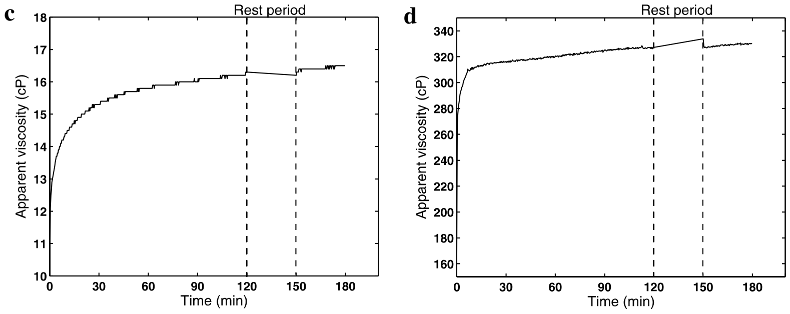


0.5g at $80s^{-1}$ 1.0g at $80s^{-1}$

Fig. 6. Selection of thixotropy plots (time versus viscosity) illustrating rheopectic behaviour for maltodextrin-based thickener for shear rates of 20 and 80 s^{-1}. Samples are subjected to a constant shear rate at constant temperature of 20.0 °C. (a) 0.5 g at 20 s^{-1}, (b) 2.0 g at 20 s^{-1}, (c) 0.5 g at 80 s^{-1}, (d) 1.0 g at 80 s^{-1}.



0.5g at $200s^{-1}$ 2.5g at $200s^{-1}$



0.5g at $400s^{-1}$ 2.5g at $400s^{-1}$

Fig. 7. Selection of thixotropy plots (time versus viscosity) illustrating rheopectic behaviour for maltodextrin-based thickener for shear rates of 200 and 400 s^{-1}. Samples are subjected to a constant shear rate at constant temperature of 20.0 °C. (a) 0.5 g at 200 s^{-1}, (b) 2.5 g at 200 s^{-1}, (c) 0.5 g at 400 s^{-1}, (d) 2.5 g at 400 s^{-1}.

ular orientations during collisions, which forms more bonds. This creates a more complex three-dimensional structure. The equilibrium between the non-structured and structured leans further to structured, meaning that shearing these samples causes an increase in viscosity.

A contrasting hypothesis can be drawn by considering the analogy of gelatinisation with shearing. Gelatinisation is the process that happens to starch fluids when heated. The heat causes the hydrogen bonds to break and the starch granules to swell. When the kinetic energy of the water molecules becomes sufficient to overcome the attraction between the hydrogen-bonded starch molecules within the granule, water molecules can penetrate the starch granules causing the granules to swell. Since the samples are very concentrated and are subjected to large shearing forces, the energy produced may be enough to mimic heating causing hydrogen bonds to break or the mechanical shearing forces may be shearing the granules open. The increase in viscosity of a starch suspension upon cooking is due to the fact that the liquid that was initially outside, separating the individual granules, is now immobilised inside the granule. This may be what is occurring when the sample is sheared. The suspension has a high viscosity because the inflated grains impede the flow of the water outside of the granules and amylose molecules leach out of the granules into solution.

4.2. Maltodextrin-based thickener

Figs. 6 and 7 illustrate the typical rheopectic behaviour exhibited by the maltodextrin thickener. The samples thicken at an inverse exponential rate and appear to saturate. It has been shown that the maltodextrin thickener behaves the same way regardless of exposure to shear or remaining at rest (Dewar & Joyce, in press). The rest period has little effect on the viscosity. The viscosity extrapolated from the 120 min mark to the 150 min mark (post-rest period) is not significantly different to the actual viscosity. In some cases such as in Figs. 6b and 7b the rest period allows for a large yield stress to form but this is quickly overcome and the flow viscosity returns to pre-rest period extrapolation.

5. Conclusion

The thixotropic behaviour of the maize starch-thickeners used in dysphagia therapy are shown to be shear rate dependent and also concentration dependent. The maltodextrin-based thickener is solely rheopectic and along with our previous work (Dewar & Joyce, in press), we have shown that this behaviour is exhibited with or without shearing.

We have shown for maize starch that the increasing viscosity via gel formation favours low or zero shear rates with low concentrated samples. Shearing is preferred however for structure formation of high concentrated samples. This is in agreement with the earlier work of Carriere (1998) regarding shear rate but not concentration. The thixotropic or rheopectic behaviour of starch dispersions is complicated and in most cases, can be toggled between both types of time-dependent behaviour by changing concentration or shear rate.

On a clinical basis, there is much to learn here, since shearing is clearly analogous to stirring. Stirring a low concentrated solution prior to consumption causes the viscosity to decrease, possibly exacerbating pulmonary aspiration. Therefore, stirring low viscosity fluids should be avoided after preparation. In contrast, high viscosity fluids can be stirred prior to consumption with no decrease in viscosity. Excessive stirring may cause the viscosity to increase too much for a given therapeutic use.

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References

Abu-Jdayil, B. (2003). Modelling the time-dependent rheological beahaviour of semisolid foodstuffs. *Journal of Food Engineering, 57*, 97–102.

Abu-Jdayil, B., Mohameed, H., & Eassa, A. (2004). Rheology of starch–milk–sugar systems: Effect of heating temperature. *Carbohydrate Polymers, 55*, 307–314.

Alloncle, M., & Doublier, J. L. (1991). Viscoelastic properties of maize starch/hydrocolloid pastes and gels. *Food Hydrocolloids, 5*, 455–467.

Axelsson, K., Asplund, K., Norberg, A., & Eriksson, S. (1989). Eating problems and nutritional status during hospital stay of patients with severe stroke. *Journal of American Dietetic Association, 89*, 109296.

Carnali, J. O., & Zhou, Y. (1996). An examination of the composite model for starch gels. *Journal of Rheology, 40*, 221–234.

Carriere, C. J. (1998). Network development during shear-thickening in semidilute solutions of gently solubilized starches. *Journal of Polymer Physics, 36*, 2085–2093.

Christianson, D. D., Hodge, J. E., Osborne, D., & Detroy, R. W. (1981). Gelatinization of wheat starch as modified by xanthan gum, guar gum and cellulose gum. *Cereal Chemistry, 58*, 513–517.

Dantas, R. O., Kern, M. K., Massey, B. T., Dodds, W. J., Kahrilas, P. J., & Brasseur, J. G. (1990). Effects of swallowed bolus variables on oral and pharyngeal phases of swallowing. *American Journal of Physiology (Gastrointestinal and Liver Physiology), 258*(5), G675–G681.

Dewar, R. J., & Joyce, M. J. (2005). Time-dependent rheology of starch thickeners and the clinical implications for dysphagia therapy. *Dysphagia* (in press).

Dintzis, F. R., & Bagley, E. B. (1995). Shear-thickening and transient flow effects in starch solutions. *Journal of Applied Polymer Science, 56*, 637–640.

Doublier, J. L., Llamas, G., & Paton, D. (1987). A rheological investigation of oat starch pastes. *Cereal Chemistry, 64*, 21–26.

Ekberg, O., Liedberg, B. O., & Owall, B. (1986). Barium and meat a comparison between pharyngeal swallow of fluid and solid boluses. *Acta Radiology Diagnosis, 27*, 701–704.

Eliasson, A. C. (1986). Viscoelastic behavior during the gelatinization of starch. *Journal of Texture Studies, 17*, 253–265.

Figoni, P. I., & Shoemaker, C. F. (1983). Characterization of time-dependent flow properties of mayonnaise under steady shear. *Journal of Texture Studies, 14*, 431–442.

Funami, T., Katoaka, Y., Omoto, T., Goto, Y., Asai, I., & Nishinari, K. (2005). Effects of non-ionic polysaccharides on the gelatinization and retrogradation behaviour of wheat starch. *Food Hydrocolloids, 19*, 1–13.

Glicksman, M. (1969). Chapter2: Function of gums in food products. In *Gum technology in the food industry* (pp. 1555). New York: Academic Press.

Goulding, R., & Bakheit, A. M. O. (2000). Evaluation of benefits of monitoring fluid thickness in the dietary management of dysphagic stroke patients. *Clinical Rehabilitation, 14*, 119–124.

Holdsworth, S. D. (1993). Rheological models used for the prediction of flow properties of food products: A literature review. *Transactions Institute of Chemical Engineering, 71*, 139–179.

Keetels, C. J. A. M., van Vliet, T., & Walstra, P. (1996). Gelation and retrogradation of concentrated starch systems: Parts 1,2 and 3. *Food Hydrocolloids, 10*, 343–368.

Langmore, S. E., Skarupski, K. A., Park, P. S., & Fries, B. E. (2002). Predictors of aspiration pneumonia in nursing home residents. *Dysphagia, 17*(4), 298–307.

Langmore, S. E., Terpenning, M. S., Schork, A., Chen, Y., Murray, J. T., Lopatin, D., et al. (1998). Predictors of aspiration pneumonia: how important is dysphagia?. *Dysphagia 13*(2), 69–81.

Lazarus, C. L., Logemann, J. A., Rademaker, A. W., Kahrilas, P. J., Pajak, T., & Lazar, R. e. a. (1983). Effects of bolus volume, viscosity, and repeated swallows in nonstroke subjects and stroke patients. *Archives of Physical Medicine and Rehabilitation, 74*(10), 1066–1070.

Logemann, J. (1983). *Manual for the videofluoroscopic study of swallowing* (2nd ed.). Pro-Ed Inc..

Mann, G., Hankey, G. J., & Cameron, D. (1999). Swallowing function after stroke: Prognosis and prognostic factors at 6 months. *Stroke, 30*, 744–748.

Marik, P. E. (2001). Aspiration pneumonitis and aspiration pneumonia. *New England Journal of Medicine, 344*(9), 665–671.

Meng, Y., & Rao, M. A. (2005). Rheological and structural properties of cold-water-swelling and heated cross-linked waxy maize starch dispersions prepared in apple juice and water. *Carbohydrate Polymers, 60*, 291–300.

Miller, J. L., & Watkin, K. L. (1996). The influence of the bolus volume and viscosity on anterior lingual force during the stage of swallowing. *Dysphagia, 11*, 117–124.

Mujumdar, A., Beris, A. N., & Metzner, A. B. (2002). Transient phenomena in thixotropic systems. *Journal of non-Newtonian Fluid Mechanics, 102*, 157–178.

Nguyen, Q. D., Jensen, C. T. B., & Kristensen, P. G. (1998). Experimental and modelling studies of the flow properties of maize and waxy maize starch pastes. *Chemical Engineering Journal, 70*, 165–171.

Rao, M. A., Okechukwu, P. E., Da Silva, P. M. S., & Oliveira, J. C. (1997). Rheological behavior of heated starch dispersions in excess water: Role of starch granule. *Carbohydrate Polymers, 33*, 273–283.

Reimers-Neils, L., Logemann, J., & Larson, C. (1994). Viscosity effects on EMG activity in normal swallow. *Dysphagia, 9*(2), 101–106.

Sajjan, S. U., & Rao, M. R. R. (1987). Effect of hydrocolloids on the rheological properties of wheat starch. *Carbohydrate Polymers, 7*, 395–402.

Shaw, D. J. (1999). *Colloid and surface chemistry*. Oxford: Butterworth-Heinemann.

Sherman, P. (1988). *Food structure its creation and evaluation: The sensory-rheological interface*. Oxford: Butterworths-Heinemann.

Smith, C. H., Logemann, J. A., Burghardt, W. R., Carrell, T. D., & Zecker, S. G. (1997). Oral sensory discrimination of fluid viscosity. *Dysphagia, 12*, 68–73.

Steffe, J. F. (1996). *Rheological methods in food process engineering*. New York: Freeman Press.

Tarrega, A., Velez-Ruiz, J. F., & Costell, E. (2005). Influence of milk on the rheological behaviour of cross-linked waxy maize and tapioca starch dispersions. *Food Research International, 38*, 759–768.

Tattiyakul, J., & Rao, M. A. (2000). Rheological behavior of cross-linked waxy maize starch dispersions during and after heating. *Carbohydrate Polymers, 43*, 215–222.

Tiu, C., & Boger, D. V. (1974). Complete rheological characterisation of time-dependent food products. *Journal of Texture Studies, 5*, 329–338.

Weinberg, A. D., & Minaker, K. L. (1995). Council on scientific affairs, american medical association, dehydration: evaluation and management in older adults. *The Journal of the American Medical Association, 274*, 1552–1556.

Weltman, R. N. (1943). Breakdown of thixotropic structure as a function of time. *Journal of Applied Physics, 14*, 343–350.

Wood, F. W. (1968). *Psychophysical studies on the consistency of liquid foods in Rheology and texture of foodstuffs*. Kent Staples Printers Ltd.

Yang, H., Irudayaraj, J., Otgonchimeg, S., & Walsh, M. (2004). Rheological study of starch and dairy ingredient-based food systems. *Food Chemistry, 86*, 571–578.

Yoshimura, M., Takaya, T., & Nishinari, K. (1996). Effects of konjac-glucomannan on the gelatinization and retrogradation of corn starch as determined by rheology and differential scanning calorimetry. *Journal of Agricultural and Food Chemistry, 44*, 2970–2976.

Zobel, H. F., & Stephen, A. M. (1995). Chapter 2: Starch: structure, analysis, and application. In *Food polysaccharides and their Applications*. New York: Marcel Dekker.