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Carbohydrate Polymers 56 (2004) 235–242
Carbohydrate Polymers
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Rheological properties of fermented finger millet (*Eleucine coracana*) thin porridge

Nelson K.O. Ojijo[a,b], Eyal Shimoni[b,*]

[a]*Department of Food Science and Technology, Jomo Kenyatta University of Agriculture and Technology, P.O. Box 62000, Nairobi, Kenya*
[b]*Department of Biotechnology and Food Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel*

Received 2 July 2003; revised 3 February 2004; accepted 20 February 2004

Available online 22 April 2004

Abstract

Effects of flour solids concentration, cooking time, and temperature on yield stress and apparent viscosity of fermented finger millet pastes were investigated. Static yield stress of pastes increased linearly with cooking time, was independent of flour solids concentration below 4.5%, and increased almost exponentially beyond this concentration. The static yield stress increased with increase in temperature in pastes boiled for 10 min, but decreased in pastes boiled for 1 h. The viscosity curves exhibited shear-thinning behavior and were adequately predicted using Cross equation. Apparent (Bingham) yield stress, derived from Cross parameters, was compared with the static yield stress for various boiling times. Cross parameters displayed bi-phasic temperature dependence in samples boiled for 60 min, with the critical temperature at around 40 °C. Results are explained in terms of starch granule swelling, amylose solubilization, and interactions between the dispersed and dispersing paste phases.

Keywords: Finger millet; Thin porridge; Starch; Amylose; Rheological behavior

1. Introduction

Fermented and non-fermented thin porridges made from cereals, singly or in composite with legumes or root crops, are traditional products that provide food security to communities in many countries. Apart from their extensive use as refreshments for adults, thin porridges also serve as complementary foods for infants (Anonymous, 1991; Griffith, Castell-Perez, & Griffith, 1998; Michaelsen, 1998) and as dietary adjuncts for convalescents. Fermentation, either spontaneously or by deliberate inoculation, is often necessary to eliminate pathogenic microflora, denature cyanogenic glycosides and mycotoxins, improve digestibility and nutritional value, and impart flavor (Holzapfel, 2002; Motarjemi, 2002). Of significance to the rheology of cooked paste is the amylolytic degradation of starch in the fermenting slurry. For finger millet, this reportedly leads to over 6% reduction in starch content over a 48-h fermentation period (Antony, Sripriya, & Chandra, 1996).

Quality characteristics of thin porridges involve nutritional, microbiological and sensory aspects. Sensory attributes have to do with flavor and mouthfeel, the latter being dependent on rheological behavior of the product. As gastro-rheological foods (Larson, 1999), the acceptability and stability of thin porridges depend on rheological characteristics. This is borne out in many ways, viz. adults prefer a smooth and 'free-flowing' consistency, infants require thin consistency but more energy density, and sedimentation and retrogradation-induced thickening in rested and cooled pastes are undesirable. Steady shear rheological data like apparent viscosity at specified shear rates or yield stress could afford direct correlation with sensory quality (Kokini, Kadane, & Cussler, 1977; Shama, Parkinson, & Sherman, 1973). For instance, foods with yield stress higher than 50 Pa have been reported to exhibit mouthfeel characteristics described as grainy, sticky, or waxy (de Bruijne, Hendrickx, Alderliesten, & Looff, 1993). In this way, rheological data enables the assignment of physically intelligible variables to otherwise esoteric sensory descriptors of product quality.

Structurally, thin porridges are a three-dimensional pasty network of flour particles and swollen starch granules

* Corresponding author. Tel.: +972-48292484; fax: +972-48293399.
E-mail address: eshimoni@tx.technion.ac.il (E. Shimoni).

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doi:10.1016/j.carbpol.2004.02.007

embedded in a dispersing gel phase of predominantly solubilized amylose molecules. Like other starchy pastes, the factors governing their rheological behavior include structure of the amylose matrix, rigidity and swelling of starch granules and flour particles, the volume fraction and shape of the granules and particles, and the granule–amylose matrix interactions (Morris, 1986). Extent of particle and granule crowding in the dispersed phase and the gelatinous characteristics of the dispersing phase in the three-dimensional network combine to influence, for example, the yield stress and viscosity curves of thin porridges. The three-dimensional paste structure may, in turn, be influenced by preparation and use conditions such as flour type, particle size, cooking time, solids fraction, fermentation, and temperature. This study was undertaken to determine the influence of flour solids, cooking time, and temperature on yield stress and viscosity curves of fermented finger millet thin porridge. When correlated with sensory responses, the findings could be used to identify rheological parameters that directly relate to quality and thus serve as a basis for objective product quality monitoring or optimization, and process design.

2. Experimental

2.1. Sample preparation

A sample of dry finger millet grains (*Eleucine coracana*) was obtained from a farm in Western Kenya. The sample was thoroughly washed in tap water and then tunnel-dried on stainless steel trays using hot air at 70 °C/3.2%RH. The dried grains were placed in double-walled polyethylene bags, heat-sealed, and stored in a cold room at 15 °C until used. Disc attrition Laboratory Universal Mill C100 LU (Alpine, Augsburg, Germany) was used for milling the samples.

2.2. Flour composition and particle size distribution

Pertinent flour components were obtained as follows: total solids by drying in vacuum oven at 70 °C to constant weight, crude ash by dry-ashing at 550 °C, amylose by DSC method (Mestres, Matencio, Pons, Yajid, & Fliedel, 1996; Osundahunsi, Fagbemi, Kesselman, & Shimoni, 2003) involving the formation of amylose-L-α-lysophosphatidylcholine complex, and starch content of whole flour was estimated on the basis of the amylose contents of flour and pure starch (extracted by the method of Hoover & Vasanthan, 1992), as follows

$$\%\text{starch} = \frac{\Delta H_{\text{flour}}}{\Delta H_{\text{starch}}} 100 \quad (1)$$

where ΔH is the DSC enthalpy of complex formation during cooling. Particle size distribution was determined using Coulter model LS230 (Coulter Corporation, Miami, USA) laser diffraction counter.

2.3. Slurry fermentation and preparation of paste

The accelerated natural lactic fermentation or back-slopping method (Masha, Ipsen, Petersen, & Jakobsen, 1998; Onyango, Okoth, & Mbugua, 2000) was used. Slurry having 7.5 g of finger millet flour and 15 g of double distilled water was prepared in a 50-ml conical flask. The flask was wrapped with aluminium foil and then incubated at 30 °C for 48 h. Thereafter, 10% (2.25 g) of the spontaneously fermented slurry was used to inoculate fresh slurries (each 22.5 g), which were then incubated at 30 °C for another 48 h. The final pH of fermenta were all above 4.0 (mean = 4.40) with adequate reproducibility (SD = 0.19). This range of variability was consistent even in different batches of fermenta. Fermented slurry was diluted with de-ionized water and then heated under reflux over an electric hot plate. A magnetic stirrer was used to moderately agitate the slurry until boiling when the paste was left to boil for the appropriate duration. The paste was then quenched in running tap water and immediately introduced into the rheometer cup or used for other analyses.

2.4. Swelling power and solids loss

The method of Chen, Lai, and Lii (2003) was used to determine the swelling power. The cooked paste was centrifuged at 8000 rpm for 20 min to separate supernatant and the residue was weighed, then dried in vacuum at 70 °C to constant weight. Swelling power was obtained as the ratio of the weight of wet residue to that of dried residue. Total solids loss was determined by drying carefully decanted supernatant using a rotary evaporator and subsequently in an air oven at 70 °C to constant weight. Amount of amylose in the solids leachate was determined as described above.

2.5. Determination of yield stress and viscosity curves

A RheoStress® 1 rheometer (Gebrüder Haake GmbH, Karlsruhe, Germany) with a temperature control unit (F8-C25 Haake Refrigerated Circulator) and data acquisition software (Rheowin Pro-Version 2.94) was used. A Mooney-Couette concentric cylinder sensor with gap 1.4 mm was used. The sample was slowly transferred into the rheometer cup maintained at a specific temperature and then left for a minimum of 45 min to equilibrate to the experimental temperature, and to recover structural degradation incurred during pouring. Flow curves were obtained over the sample temperature range 20–60 °C (±0.03 °C). A thin layer of light paraffin oil was applied on to the exposed sample surface to prevent evaporative loss. The static yield stress (σ_{os}) was obtained from a double logarithmic plot of shear stress versus shear strain as the point of intersection of two tangents drawn to the first

and second regions (Bhattacharya, 1999) as shown in Fig. 1. Apparent viscosity values were also obtained in controlled stress rotation ramp mode for 6 min over the shear rate range 0–1200 s^{-1}, within the operational range of the equipment.

A double logarithmic plot of apparent viscosity (η) versus shear rate ($\dot{\gamma}$) is known as a viscosity curve (Barnes, Hutton, & Walters, 1989). The Cross model (Eq. (2)) is frequently used to describe the viscosity curves of starchy pastes and other foods (Barnes et al., 1989; Chamberlain & Rao, 1999; Ferguson & Kembłowski, 1991; Prentice, 1984)

$$\eta = \eta_f + \frac{(\eta_i - \eta_f)}{[1 + (k\dot{\gamma})^m]} \quad (2)$$

where η_i is the initial apparent Newtonian viscosity at low shear rates (Pa s), η_f is the final Newtonian viscosity at high shear rates (Pa s), k is the characteristic time (s), $\dot{\gamma}$ is the shear rate (s^{-1}), and m is a dimensionless constant. Under certain conditions, the Cross model can be approximated to the Bingham equation. If the value of m is unity (as in very non-Newtonian systems), $\eta_i \gg \eta_f$, and $k\dot{\gamma} \gg 1$, Eq. (1) simplifies to (Barnes, 1999):

$$\eta = \eta_f + \frac{\eta_i}{k\dot{\gamma}} \quad (3)$$

By multiplying every term by $\dot{\gamma}$, we have:

$$\sigma = \frac{\eta_i}{k} + \eta_f\dot{\gamma} \quad (4)$$

Re-defining the terms, Eq. (3) assumes the form of the well-known Bingham equation thus

$$\sigma = \sigma_{oB} + \eta_p\dot{\gamma} \quad (5)$$

where σ_{oB} is the apparent (Bingham) yield stress, and η_p is the plastic viscosity. Thus, yield behavior may be inferred for a fluid describable by the Cross model. The applicability of the Cross model to fermented finger millet porridge flow data was tested using a non-linear regression algorithm in SigmaPlot (Jandel Corporation, 1995). The influence of temperature on yield stress and the obtained Cross model parameters were determined using Arrhenius equation

$$P = A\exp\left(-\frac{E_a}{RT}\right) \quad (6)$$

where P is the relevant parameter, A is the pre-exponential factor with dimensions of the relevant parameter, E_a is the activation energy (kJ mol^{-1}), R is gas constant (kJ mol^{-1} K^{-1}), and T is the absolute temperature (K).

3. Results and discussion

3.1. Flour composition and particle size

The finger millet flour had 95.19% solids, 76.37% starch, 21.55% amylose, and 2.66% crude ash. Amylose content of the isolated starch was 28.20%. Particle size distributions in fermented slurry and pastes boiled for 30 and 60 min were as shown in Fig. 2. A multimodal particle size distribution was evident in the fermented slurry, but this changed into monomodal distributions in cooked pastes albeit with increasing mean particle size diameter.

3.2. Yield stress

Controlled-stress rheometry enables direct determination of the minimum stress necessary for 'instrumentally detectable flow' in fluid and plastic foods, otherwise known as the static yield stress (Larson, 1999; Steffe, 1996). The static (σ_{os}) and Bingham (σ_{oB}, derived from Cross parameters in Section 3.3) yield stresses of finger millet pastes, boiled for various time (t) intervals ranging from 5 to 25 min, are compared in Fig. 3. A linear increase in σ_{os} ($\sigma_{os} = 0.153t$, $r^2 = 0.99$) was observed for the entire range of cooking time, while σ_{oB} displayed an inflection in linearity at around 10 min of boiling. The values of σ_{os} and σ_{oB} were similar for cooking times up to 10 min, but diverged with extended cooking. Further, Fig. 4 shows the variation of σ_{os} with flour solids concentration (c) for

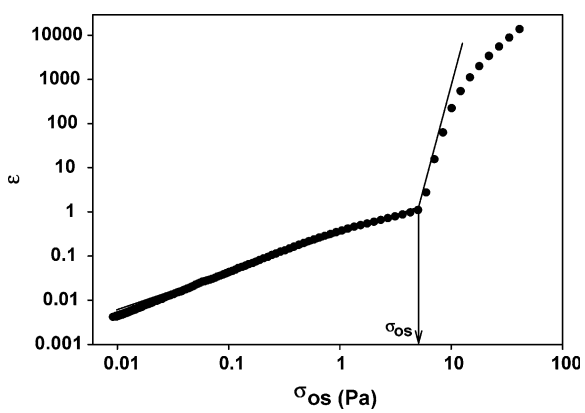

Fig. 1. Determination of static yield stress.

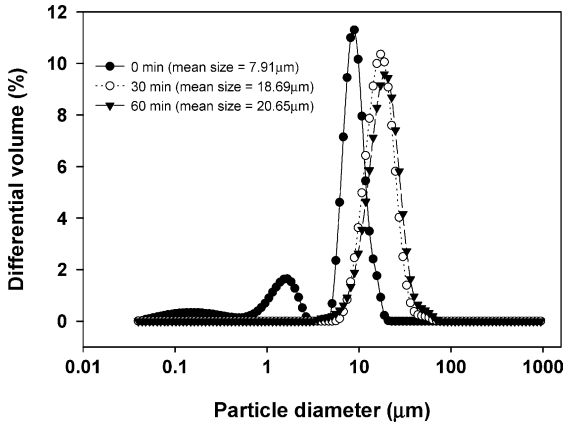

Fig. 2. Particle size distribution of finger millet slurry and pastes.

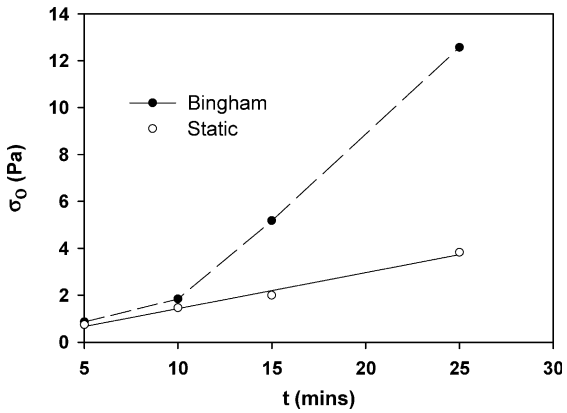

Fig. 3. Effect of cooking time on static and Bingham yield stresses of fermented finger millet pastes.

10-min cooked samples. There was no major change of σ_{os} with flour solids concentration below a concentration of about 3.5% (w/v). However, beyond this concentration, an almost exponential increase in σ_{os} occurred. At short cooking times, there was restricted granule swelling and the dispersing phase had weak gel characteristics due to limited amylose solubilization (Fig. 5). In addition, at $c \leq 3.5\%$, gelatinized starch granules and other particulates in the paste are dispersed far apart with limited inter-particle and hydrodynamic interactions. Consequently, there was no change in σ_{os}. The 3.5% solids concentration may also indicate the critical concentration for gel formation by the solubilized starch components. Yielding occurs due to deformation and slippage between layers of adjacent molecules or particles being aligned in the direction of shear (Larson, 1999). As the degree of solubilized amylose in the dispersing phase and solids concentration increased, the energy to overcome the molecular and inter-particle interactions to cause alignment in the direction of shear also increased. This led to an increase in σ_{os} (Prentice, 1984).

The variation of σ_{os} with temperature in pastes cooked for 10 min is shown in the Arrhenius plot of Fig. 6, and the associated Arrhenius parameters are given in Table 1. The σ_{os} of fermented finger millet pastes increased with increase

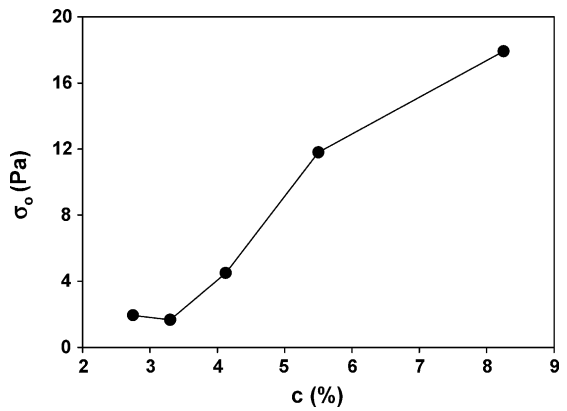

Fig. 4. Effect of flour solids concentration on static yield stress of fermented finger millet pastes.

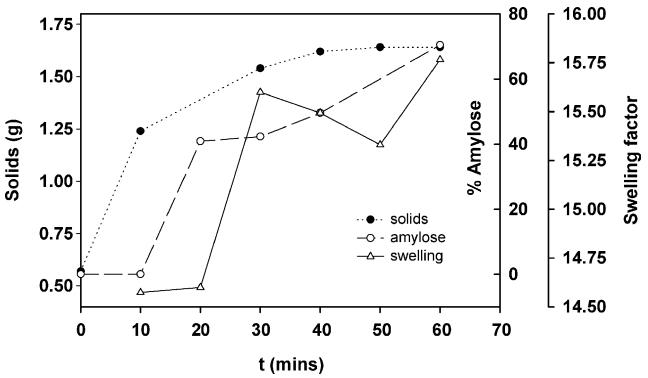

Fig. 5. Effect of cooking time on solids loss, amylose in leachate, and swelling power of finger millet pastes.

in sample temperature. This may seem anomalous since rheological properties of foods usually decrease with increase in temperature (Rao, 1999). However, in complex systems like thin porridge suspensions, the occurrence of such an anomaly is not wholly unexpected (Ferguson & Kembłowski, 1991). Repeated determinations consistently gave an overall increase in σ_{os} over the temperature range investigated here. Okechukwu and Rao (1995) reported that a 2.6% corn starch suspension attained maximum diameter ratio (an index of extent of granule swelling) during isothermal heating at 90 °C after about 50 min. Likewise, in the present case, boiling finger millet slurry for 10 min was insufficient to completely gelatinize all starch granules as shown by the changes in solids loss and swelling factor in Fig. 5. Subsequent incubation of pastes for a minimum of 45 min in the rheometer cup to effect temperature equilibration and structural recovery before running the tests might have led to further swelling of starch granules and concomitant amylose solubilization. Since yield stress values of cereal pastes depend on the extent of granule swelling (Christianson & Bagley, 1984), this might have led to the present increase in σ_{os} with sample temperature. To further pursue this line of thought, we subjected fermented finger millet slurry to boiling for 1 h under reflux and determined the σ_{os} of the resulting paste at various temperatures. The results are shown in Fig. 6 with

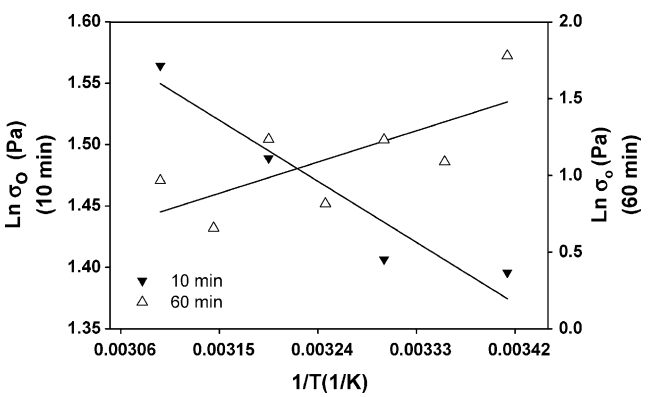

Fig. 6. Effect of temperature on static yield stress for 10 and 60 min-boiled fermented finger millet pastes.

Table 1
Arrhenius parameters for rheological properties of fermented finger millet pastes[a]

	Boiling time (min)	Temperature range (°C)	A	E_a (kJ mol^{-1})	r^2
Yield stress	10	$20 \leq T \leq 55$	1.03×10^2	−7.94	0.73
	60	$20 \leq T \leq 55$	5.10×10^2	18.78	0.51
Cross model parameters	10	$\eta_i : 20 \leq T \leq 55$	1.95×10^{12}	−15.39	0.97
		$k : 20 \leq T \leq 55$	2.58×10^{13}	−76.36	0.92
		$m : 20 \leq T \leq 55$	–	–	–
		$\eta_f : 20 \leq T \leq 55$	1.30×10^4	65.05	0.90
	60	$\eta_i : 20 \leq T \leq 55$	–	–	–
		$k : T \leq 40$	1.38×10^{10}	−50.47	0.91
		$k : T \geq 40$	1.55×10^6	46.53	0.95
		$m : T \leq 40$	6.60×10^1	10.45	0.84
		$m : T \geq 40$	9.40×10^1	−12.29	0.66
		$\eta_f : T \leq 40$	3.93×10^{12}	67.36	0.50
		$\eta_f : T \geq 40$	5.20×10^{20}	−132.8	0.98

[a]The yield stress of pastes increased with increase in sample temperature for pastes boiled for 10 min, but decreased with increase in sample temperature for pastes boiled for an hour (see explanation in text). m showed no temperature dependence in pastes boiled for 10 min; η_i did no show temperature dependence in pastes boiled for 1 h; k, m, and η_f all exhibited biphasic temperature dependent behavior in pastes boiled for 1 h with the critical temperature of transition at around 40 °C. The pre-exponential factor A takes on the corresponding units of the relevant parameter, i.e. Pa for yield stress, s for k, and so on.

the corresponding kinetic parameters in Table 1. The σ_{os} values now evidently decreased with temperature. Apparently, there was a dramatic change in the structural constitution of the three-dimensional paste network that led to a complete reversal of the temperature dependence phenomenon. Boiling the slurry for 60 min effected complete gelatinization of the starch granules as shown by a plateau in solids loss and swelling factor (Fig. 5). Subsequent sample equilibration in the rheometer cup did not lead to any further granule swelling and σ_{os}—now influenced only by the dispersing phase—decreased with increase in temperature. Thus, σ_{os} of fermented finger millet pastes may increase or decrease with temperature depending on the degree of cooking and predominant temperature sensitive mechanism. For short cooking times, the influence of temperature on dispersed granule characteristics predominates, causing an anomalous increase of σ_{os} with temperature. For extended cooking and complete gelatinization, the amylose gel phase is the predominant temperature-sensitive phase leading to the expected decrease in σ_{os} with temperature. The existence of yield behavior in thin porridges may impede sedimentation of dispersed particulate matter (Prentice, 1984), and has a psycho-rheological correspondence with 'ease-of-sipping' or the minimum suction force necessary to sip the product into the mouth.

3.3. Viscosity curves

The viscosity curves of fermented finger millet pastes were obtained at various cooking times, flour solids concentrations, and sample temperatures. All the curves conformed to the same basic pattern as represented by the curves pertaining to pastes at various flour solids concentration in Fig. 7. An initial region in which the apparent viscosity decreased with increase in shear rate, indicating shear-thinning behavior, characterized all the curves. For solids concentration below about 5.50%, a η_i region was apparent. Also evident is the fact that the shear rate at onset of shear-thinning behavior appeared to be lower the higher the flour solids concentration. According to Larson (1999), shear-thinning is an attribute of suspensions that form three-dimensional ordered structures at rest and commences when the shear rate is high enough to disturb from equilibrium the distribution of inter-particle spacing. Consequently, and in view of the present results, concentrated pastes are more susceptible to shear-thinning. A η_f region, especially at low flour concentrations, was also apparent in Fig. 7. Non-linear regression was used to fit the Cross equation to all the curves. Applicability of Cross equation in describing the viscosity curves is indicated by the solid lines ($r^2 \approx 1$). The obtained Cross parameters are plotted against flour concentration in Fig. 8. There was no change in η_i and k at $c \leq 4.5\%$. Beyond this solids concentration, there was a marked increase in both parameters (η_i reached over 230 Pa s while k attained

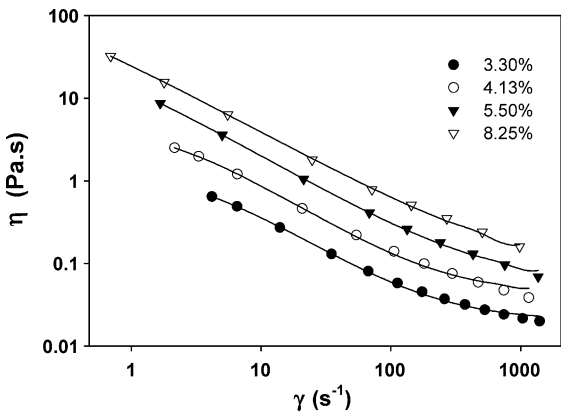

Fig. 7. Viscosity curves of fermented finger millet pastes at various flour solids concentrations.

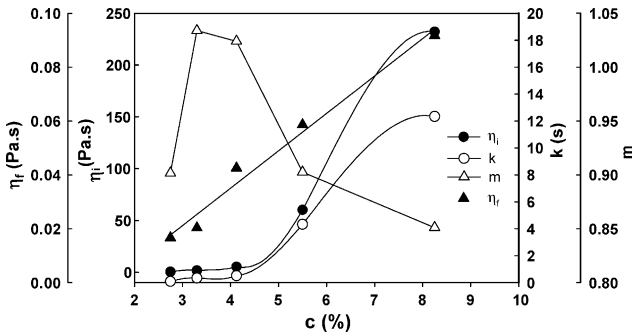

Fig. 8. Effects of flour solids concentration on Cross model parameters.

a value of about 12 s) with increase in flour concentration. The η_f values increased linearly with $c(r^2 = 0.981)$, while m had values between 0.851 and 1.024, which displayed an overall decrease with increase in c (Fig. 8). Cross (1965) derived the above equation based on the assumption that linkages between molecules are broken during shearing. Hence, shear-thinning behavior could be regarded as a rate process (Prentice, 1984). The parameter k is related to the relaxation time of the structural species responsible for shear-thinning and the onset of shear-thinning behavior (Chamberlain & Rao, 1999; Prentice, 1984). On the other hand, the parameter m is related to the flow behavior index n in the power law model (Lopes da Silva, 1994). Indeed, for systems in which $\eta_i \gg \eta_f$, the Cross equation reduces to the power law model or may be approximated to the Bingham model (Barnes, 1999; Barnes et al., 1989). Usually, m has a zero value for Newtonian fluids and a positive value below unity for shear-thinning fluids (Chamberlain & Rao, 1999). However, in non-food systems at volume fractions beyond 0.5, the value of m becomes greater than unity and can be as high as 3.5 (Larson, 1999). In the present case, the value of m was about unity and appeared to decrease at higher solids concentration.

The influence of cooking time on Cross parameters for 3.56% flour solids concentration is shown in Fig. 9. There was a dramatic decrease in all parameter values between 5 and 10 min of cooking time. Thereafter, there was a more gradual decrease with η_i and k decreasing throughout the cooking duration, while m and η_f increasing for cooking

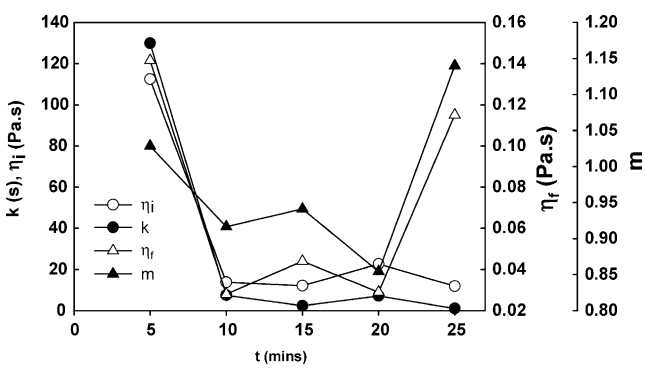

Fig. 9. Effects of cooking time on Cross model parameters.

times beyond 20 min. The cause of the initial decrease in parameter values is unclear but at extended boiling times, there is amylose solubilization and rapture of starch granules leading to loss of structure contributed by swollen granules. This may lead to decrease in parameter values. Subsequent rise in m and η_f values may be due to extra-granular structure formation in the dispersing phase by solubilized amylose molecules. This effect seemingly did not influence the values of k and η_i. As discussed previously, starch gelatinization is far from complete after 10 min of boiling finger millet slurry. As boiling progresses, the net structure contributing to shear-thinning behavior is the balance between extent of swollen granules and the development of amylose network. Whereas k and η_i seem to be influenced by the amount and degree of swollen granules, m and η_f may be related to the formation of extra-granular amylose network.

Viscosity curves were obtained at different sample temperatures for fermented finger millet pastes prepared by boiling 3.56% flour solids slurry for 10 min. The curves were fitted to the Cross model, and the temperature dependence of model parameters over the temperature range 20–60 °C were determined using the Arrhenius equation. The results are shown in Fig. 10, with the attendant kinetic parameters in Table 1. The m parameter did not show temperature dependence. As in the case of σ_{os}, η_i and k both increased with increase in temperature, while η_f decreased with increase in sample temperature. We attribute the increase in η_i and k with sample temperature to the same starch granule swelling characteristics that engendered a similar increase in σ_{os} (Fig. 6). Based on the activation energy values (Table 1), k was the most temperature dependent parameter and η_i the least in the 10-min cooked samples. The asymptotic viscosity at high shear rates (η_f) is an indication of the extent of shear-induced structural degradation, which is greater the higher the temperature. This accounts for the decrease in η_f value with increase in temperature. Furthermore, shear stability of starch granules decreases with increase in granule swelling

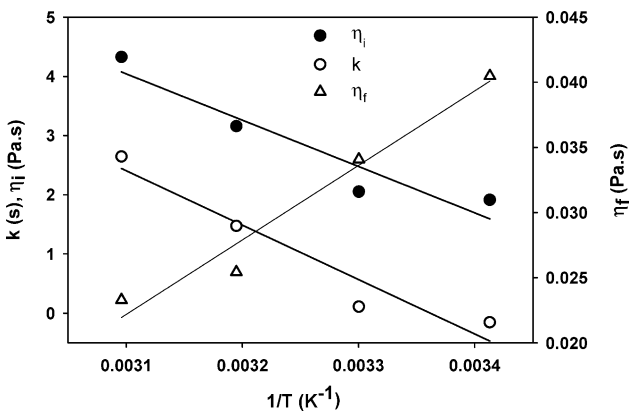

Fig. 10. Effects of temperature on Cross model parameters for fermented finger millet pastes cooked for 10 min. m parameter did not show temperature dependence in pastes boiled for 10 min.

and this led to decrease in η_f. By a similar analogy, since a high value of k shows a large shear dependent contribution to structural breakdown (Cross, 1965), it only follows that k increased with sample temperature. In addition, as discussed by Chamberlain and Rao (1999), the existence of zero shear viscosity in polysaccharide systems is due to a balance between shear-induced physical disentanglements and formation of new entanglements between the polysaccharide molecules. The equilibrium situation between these two antagonistic processes will probably shift in favor of formation of new entanglements the higher the temperature resulting in an increase in η_i.

On boiling the slurry for 60 min, the resulting paste presented a completely different picture (Fig. 11, Table 1).

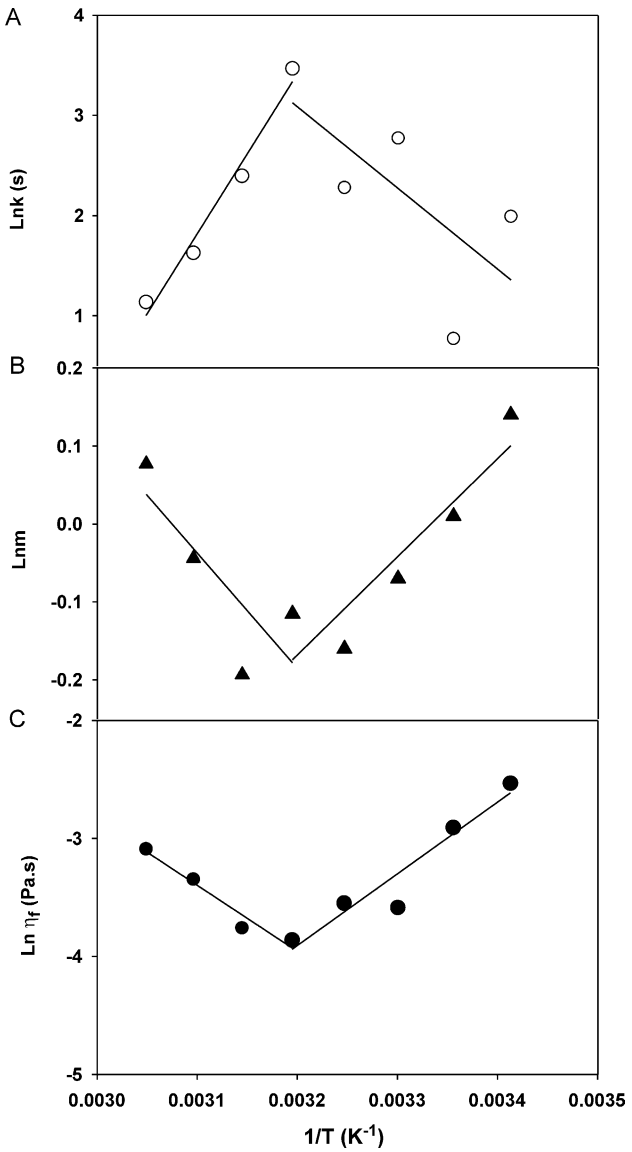

Fig. 11. Effects of temperature on Cross model parameters for fermented finger millet pastes cooked for 60 min. η_i did not show temperature dependence in pastes boiled for 60 min. Bi-phasic temperature dependence is evident in all parameters with an inflection at around 40 °C.

The initial Newtonian viscosity, η_i was temperature independent, while m became temperature dependent. Furthermore, k, m, and η_f all displayed a biphasic pattern of temperature dependence. Both m and η_f (Fig. 11B and C, respectively) decreased with temperature below about 40 °C and increased with temperature above 40 °C. The activation energy values for both phases were least for m and highest for η_f. Similarly, k (with intermediate activation energy values) decreased with temperature below 40 °C and increased above this temperature (Fig. 11A). These results suggest a complex mechanism of temperature dependence. In simple systems, the change in viscosity with temperature is mainly due to the change in viscosity of the dispersing phase (Barnes et al., 1989). However, as discussed above, finger millet thin porridge is a more complex system with different temperature sensitive interactions. In polymeric and colloidal systems, structural changes in the continuous phase as well as temperature sensitive interactions in the dispersed phase may result in increase or decrease of flow properties with temperature (Barnes et al., 1989; Ferguson & Kembłowski, 1991). In the present case, it is possible that thermo-reversibility of amylopectin gels in the pastes beyond 40 °C may be one factor that led to the observed biphasic temperature dependence in samples cooked for 60 min. With such severe thermal treatment, there could be significant solubilization of amylopectin. Significant retrogradation has been shown to occur in solubilized amylopectin chains within 1 h at 25 °C (Bello, Waniska, Gomez, & Rooney, 1995). In addition, differential scanning calorimetry reveals that melting endotherms of retrograded amylopectins have an onset temperature of transition in the range 35–45 °C (Gudmundsson, 1994; Jouppila & Roos, 1997; Miles, Morris, Orford, & Ring, 1985; Ortega-Ojeda & Eliasson, 2001). This temperature range coincides with the critical temperature at which the Arrhenius plots of the Cross parameters reversed as shown in Fig. 11.

4. Conclusions

Steady shear rheological properties of fermented finger millet paste have been discussed. Static yield stress of paste increased with flour concentration in an exponential fashion, and displayed 'anomalous' increase with temperature. This was explained in terms of starch granule swelling of the dispersed phase. Apparent viscosity curves were dependent on flour solids concentration, temperature and cooking time, and exhibited shear-thinning characteristics. The Cross equation was applicable in describing the viscosity curves. The parameters η_i and k showed an exponential variation with flour concentration, η_f increased linearly with concentration, while m had values about unity, which showed an overall decrease with flour concentration. In pastes boiled for 10 min, m did not show temperature dependence, while σ_{os}, k, and η_i all increased with increase in temperature; but η_f decreased

with temperature. The increase of certain Cross parameter values with temperature was attributed to increased granule swelling at higher sample incubation temperatures. On cooking for 60 min, σ_{os} decreased with temperature, η_i did not show temperature dependence, while k, m and η_f all showed bi-phasic temperature dependence. Above 40 °C, m and η_f increased with temperature while k decreased with temperature. The reverse occurred for all the parameters below 40 °C.

Acknowledgements

Author NKOO gratefully acknowledges the generosity of the Israeli Government and UNESCO for the fellowship grant that enabled this work at the Department of Biotechnology and Food Engineering, The Technion—Israel Institute of Technology, Israel. We also thank Dr Sigal Eichler for DSC analysis, and the reviewer for very constructive comments.

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