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Steady state flow behaviours of extruded blend of rice flour and soy protein concentrate

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Abstract

Rheological properties in terms of steady state flow behaviours of extruded dispersions (rice flour/soy protein concentrate blend), were investigated using dynamic rheometry. The effects of concentration (2%, 5%, 7%, 9% and 11%) and temperature (25–70 °C) on the rheological parameters (yield stress, flow behaviour index) of the non-expanded pellet blend (12.5% protein) were determined using common rheological models. Steady-shear viscosities in a range of shear rate from 0 to 500 s^{-1} were observed as a function of concentration and temperature. From typical curves showing the dependence of shear stress on shear rate, it could be observed that all suspensions exhibited a non-Newtonian and pseudoplastic behaviour. The model that best fitted the experimental data at all temperatures and concentrations was the Herschel–Bulkley model.

Keywords: Extrusion cooking; Extruded blend dispersion; Rheological models; Apparent viscosity

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important foodstuffs for people in many countries, especially in Oriental countries, and soy bean (*Glycine max*) is also consumed locally in different forms. Since rice and soybean mutually supplement each other in terms of limiting amino-acids, blending of the two in the correct ratio generates a good protein source that should alleviate the negative features caused by malnutrition among vulnerable people in developing countries.

Rheological properties of food dispersions are of great importance for several reasons especially in sensory evaluation, quality control, process design flow equipment (mixing, pumping, heating, cooling), new product development, (Abdelrahim, Ramaswamy, Doyon, & Toupin, 1994; Dail & Steffe, 1990), process scale-up, and optimization of process variables. Numerous studies have been conducted on the rheological properties of various food dispersions (Baby Latha, Bhat, & Bhattacharya, 2002; Bagley & Christianson, 1983; Bhattacharya & Bhattacharya, 1994; Sandaya Rani & Bhattacharya, 1985, 1989; Wang & Sun, 1999) whereas, Battacharya and Bhat (1997) evaluated the flow behaviour of rice–blackgram suspensions and suitability of the rheological model in addition to the rheology of Bengal gram flours (Bhattacharya, Bhat, & Raghuveer, 1992). The majority of the authors concluded that the power law model was best for describing the studied materials.

Extrusion cooking can be used to produce foods that are nutritionally balanced or enriched (weaning foods, meat replacers, animal feeds and dietetic foods). There is a possibility of using soy protein concentrate (SPC) in combination with rice flour (RF), not only to provide a useful alternative in highly nutritious food products, but also to improve the physicochemical, functional and sensory characteristics of the products. Extruded cereal blends are a promising nutritious vehicle for incorporation of soy, with breakfast cereals and snack foods leading the category.

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It is reported that soy protein concentrate has specific functional properties that enable it to modify the physical properties of food products. During extrusion cooking, starch or protein undergoes physicochemical changes (such as starch gelatinization, protein denaturation and hydrogen bond rupture) that result in new functional properties and substantial changes leading to greater or partial molecular disorganization. After extrusion, when starch dispersions are heated, starch polymer solubilization occurs and the properties of continuous phase and dispersed phases are influenced. In addition, according to D'Egidio, Stefanis, Fortin, Nardi, and Sgrulletta (1984), rheological properties of food pastes were improved due to interactions between wheat protein, gliadin fraction and amylose. Moreover, it was reported that the viscosity was significantly affected by the increase of protein content in blends with different amylose contents (Goel & Kokini, 1992). It was recently reported that the interaction of starch and protein plays an important role in macroscopic properties of food products in terms of flow, stability, texture and mouth feel (Ravindra, Genovese, Foegeding, & Rao, 2004).

As the material being extruded under high moisture conditions undergoes thermal processing during the extrusion process, there is significant change in apparent viscosity resulting from polysaccharide-protein interaction and food protein gelation. Therefore, it was necessary to have a basic knowledge of the influence of shear rate and temperature on the rheological behaviour of the extrudates resulting from the rice–soy protein blend.

The aim of the present study was to investigate the effect of concentration, temperature of the extruded blend suspensions on the rheological properties in order to study the effects of protein concentration on the taste and texture of the extruded blends at a later date. The rheological properties are considered with reference to steady state-flow behaviour.

2. Materials and methods

2.1. Materials

Soy protein was purchased from Guan Li Ke Trade Company (Jinan; China). Long-grain, high-amylose commercially milled rice (apparent amylose content $29.63 \pm 0.47\%$) was purchased from a local Wuxi market (China). The milled rice was ground to flour in a hammer mill, passed trough a 60-mesh sieve (British standard) and was prepared by premoistening in a ribbon blender before extrusion. The moisture content was equilibrated at 30% for the blend made of rice flour and soy protein concentrate (SPC). SPC was added to achieve 12.5% protein content in the blend after extrusion cooking. Moisture, protein and fat contents were measured according to Association of Official Analytical Chemists (1980). All analyses were the means of three replicates.

The material was delivered into the extruder barrel through a feeder calibrated for the desired feed rate and processed in a corotating twin-screw extruder (DS32-II, Jinan Saixin Food Machinery, Shandong, China), consisting of three independent zones of controlled temperature in the barrel. The length-to-diameter (L/D) ratio was ≈20:1. The temperature profiles in the feed and compression metering zones were kept constant at 60 and 70 °C, respectively, and the die head temperature was maintained at 110 °C. From preliminary tests, a screw speed of 60 rpm was selected. The die opening had five elliptical apertures with a long axis length of 5.0 mm. There was no expansion at the die and the pellets were collected after stable operations were established; extrudates were collected and dried in an air oven at 45 °C for 18 h. Extruded material was stored at 4 °C in plastic bags for further analysis. All the experiments were conducted in triplicate.

2.2. Extrudate suspensions preparation

Rheological measurements during heating and cooling cycles of the extruded blend suspensions were determined using an AR 100 Rheometer (TA Instruments, UK) with parallel-plate geometry of 40-mm diameter and gap geometry 1000 μm. They were loaded onto the ram of the rheometer and covered with a thin layer of low-density silicon oil to minimize evaporation. Rheological properties were described in terms of shear rate vs. shear stress and were obtained using the software of the analysis programme. Extrudate suspensions at different concentrations were scanned from 20 to 95 °C during heating and from 95 °C to the desired temperature (25, 40, 55 and 70 °C) during cooling at a rate of 5 °C/min. Then, they were subjected to increasing shear rates (forward direction) from 0 to 500 s^{-1} and/or backward direction to obtain data sets comprising shear rate, shear stress, and apparent viscosity values. All rheological measurements were conducted in duplicate. The software supplied by the equipment manufacturer was used to examine the suitability of common rheological models with reference to the standard errors.

2.3. Rheological models

Shifang (2000) reported that, in order to perform a quantitative comparison of materials, fitting of the experimental data to some forms of best fit mathematical equation or models is generally required. Thus, the following common models were used to test their applicability to the flow behaviour of extrudate dispersion systems.

1. Herschel–Bulkley model:

$$\sigma = \sigma_{\mathrm{oHB}} + K_{\mathrm{HB}}\dot{\gamma}^{\mathrm{nHB}} \tag{1}$$

2. The power-law or Ostwald-de-Waele model:

$$\sigma = kP(\dot{Y})^{nP} \tag{2}$$

3. Bingham plastic model:

$$\sigma = \sigma_{\mathrm{B}} + n_{\mathrm{B}}\dot{\gamma} \tag{3}$$

4. Casson model:

$$\sqrt{\sigma} = \sqrt{\sigma_c} + n_c\sqrt{\dot{\gamma}} \quad (4)$$

where σ is the shear stress in (Pa), $\dot{\gamma}$ is the shear rate in (1/s). The parameters σ_o, k, and n, are yield stress (Pa), consistency coefficient (Pa s), and flow behaviour index (dimensionless), respectively; the subscripts HB, P, B and C stand for Herschel–Bulkley, Power Law, Bingham and Casson models.

3. Results and discussion

3.1. Chemical composition

Table 1 shows results for proximate composition of rice flour, soy protein concentrate, and extruded blend pellets. Addition of SPC to rice flour increased the protein content from 6.71% to 12.5%. However, fat content in extruded blend pellets was lower than that of untreated flour, probably due to the formation of amylose–lipid complexes. Our preliminary analysis, using differential scanning calorimetry (DSC), showed that there was an endodermic peak at around 101 °C which resulted from the formation of amylose–lipid complexes.

3.2. Rheological characteristics of extruded blend pellets

3.2.1. Characterization of the flow curve: shear rate vs. shear stress

The shear rate and shear-stress data were fitted to different models, namely Herschel–Bulkley (H–B), Power Law (P-L), Casson, and Bingham plastic. Fig. 1 shows a representative flow curve shear rate vs. shear stress at different temperatures 25 (1) and 70 °C (2). Reference to the classification of time-independent flow behaviour of fluid foods, shows that all the curves exhibited shear-thinning behaviour, that is a curvature downwards on the shear rate axis and all samples had a non-Newtonian and pseudoplastic behaviour.

A pseudoplastic behaviour was observed and this suggested that all starch granules were sufficiently swollen, probably due to the extrusion process, and could be deformed under the applied shear force. However, the effect of added protein on the swelling behaviour of starch granules should be determined in coming studies. The pseudoplastic behaviour of gelatinized maize, waxy maize and wheat starch pastes was also reported by Nguyen, Jensen, and Kristensen (1998). The best fit curve is judged by standard error (not shown) with the AR 100 Rheometer, and, the greater the standard error, the worse was the fit; therefore Fig. 1 provides the representative flow curves representing the H–B model at all temperatures in the forward direction.

3.2.2. Effect of concentration at different temperatures

When the effect of concentration was examined, it was observed that shear stress increased with increasing shear rate and the extent of downward bending curvature decreased as the concentration of extruded blend suspensions was decreased. The lowest standard errors obtained with the H–B model, compared to P-L, Bingham and Casson models, show the ability of the former model to correlate the shear rate vs. shear stress data for the extruded blend suspensions.

A plot of shear stress vs. viscosity in logarithmic coordinates (not shown) displayed curves with a slight upward curvature toward the low shear stress, and this indicates the presence of a yield stress (Bagley & Christianson, 1983). Doublier, Colonna, and Mercier (1986) suggested that this tendency is generally displayed by suspensions of swollen particles. Therefore, the shear rate-shear stress data were fitted well to the H–B model rather than to the conventional power low model.

Table 1
Chemical composition of rice flour, SPC, and extruded blend

	Rice flour	SPC	Extruded blend
Moisture (% db)	12.40 ± 0.21	5.22 ± 0.08	9.89 ± 0.13
Protein (%) (NX6.25)	6.71 ± 0.19	69.0 ± 0.01	12.5 ± 0.33
Fat (% db)	0.41 ± 0.09	0.53 ± 0.02	0.39 ± 0.08
Ash (%)	0.39 ± 0.03	4.21 ± 0.06	0.42 ± 0.04
Carbohydrate (by difference) (%)	80.1 ± 0.97	21.0 ± 0.02	76.8 ± 0.26

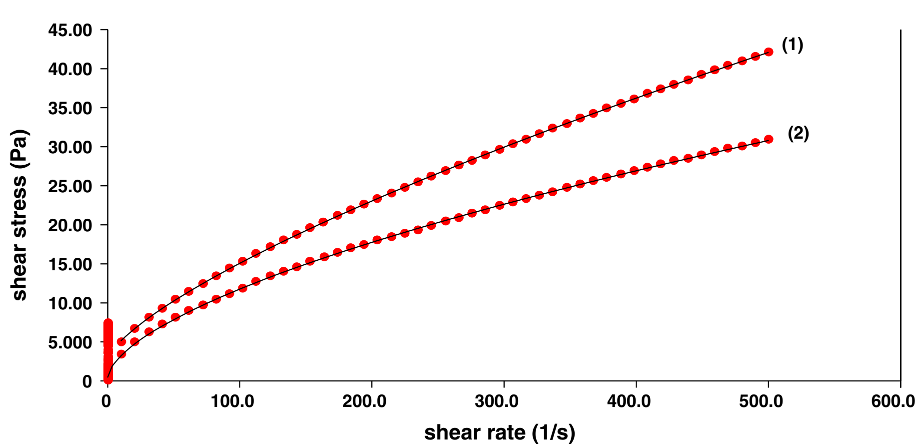

Fig. 1. Representative flow behaviour of extruded blend made of rice flour/SPC dispersions (11% w/w) at 25 °C (1) and 70 °C (2).

Furthermore, from the values of the H–B model parameters, the yield stress (σ_o) and the consistency index (k) increased with increasing of concentration at both temperatures (25 and 70 °C). Increase in k with an increase of concentration is commonly reported by researchers (Rao, 1977; Vitali & Rao, 1984). The flow behaviour index (n) fell from 0.875 to 0.723 and from 0.886 to 0.614 at 25 and 70 °C, respectively, when the concentration was increased from 2% to 11%.

Moreover, when the viscosity was represented against shear rate, it diminished as shear rate increased and it could be proved again that the extruded suspensions exhibited a shear thinning or pseudoplastic behaviour. It was observed that the variation was not linear and therefore, the extrudates suspensions were non-Newtonians fluids. The viscosity increased with increasing of extrudates concentration (over the concentration range of 2–11%) from 5.29 to 150.1 MPa s and from 4.33 to 116.3 MPa s at 25 and 70 °C, respectively (Table 2). A similar observation has been made by Prakash, Haridasa Rao, Susheelamma, and Prabhakar (1998) in the case of native and steamed wheat flour suspensions. Moreover, we assume that the decrease in viscosity should also be influenced by the dissociation of non-covalent bonds between the soluble SPC. The fits of the experimental results given in Fig. 2 to Eq. (1) are illustrated by continuous lines and they represent the experimental data quiet well.

3.2.3. Effect of temperature on rheological constants

Typical flow rheograms, shear stress vs. shear rate, of extruded suspensions heated at 95 °C and cooled at 25, 40 and 55 °C, respectively, showed the same trend as in Fig. 1. All rheological constants (yield stress, flow behaviour index (n), consistency index (k) and apparent viscosity) obtained from the flow curve were influenced by the operation temperature and they can explain the data well.

Yield stress (σ_o) represents the minimum stress that is needed to initiate flow (Christianson & Bagley, 1984). Although there were no appreciable values of the yield stress, they ranged from 4.68×10^{-2} to 5.849×10^{-3} Pa for the entire range of temperature (25–70 °C). The highest value was obtained at low temperature (Fig. 3A), i.e., σ_o decreased with increasing of temperature. No yield points were detected by Bagley and Christianson (1983) for the 10% cooked wheat starch dispersion at 60 °C. In fact, the cooking temperature history, shear degradability and the method of measurement play important roles in polymer exudate materials in the continuous phase at high temperature, which appear to influence the formation of a structure in the dispersion, detectable as a yield value.

As there is a general tendency for the viscosity to decrease with increasing temperature, consistency index, k, also decreased with increasing of temperature (Fig. 3B) (Rao, 1977; Vitali & Rao, 1984) and k ranged from 5.692×10^{-2} to 2.567×10^{-2} Pa s.

Flow behaviour index (n), which indicates the behaviour of the fluid, also showed a trend opposite to the consistency index; n varied from 0.7968 to 0.8296 for the range of temperature studied. All the values of n were <1 and this is also an indicator of their pseudoplastic shear-thinning behaviour (Fig. 3C).

Table 2
Apparent viscosity (MPa) of dispersion at shear rate 100 s^{-1}

Concentration (% solid)	Temperature (°C)	
	25	70
2	5.29	4.33
5	22.84	16.22
7	45.36	34.73
9	50.65	38.76
11	150.1	116.3

3.2.4. Apparent viscosity

Apparent viscosity decreased with increase of temperature, as evidenced by the decrease of k at each level of concentration. However, there is considerable evidence that the influence of temperature on viscosity, for a liquid food, may be described by an Arrhenius-type relationship (Eq. (5)). Fig. 3D shows the Arrhenius type behaviour between the inverse absolute temperature and the experimental apparent viscosity for a 5% (w/v) extruded blend dispersion

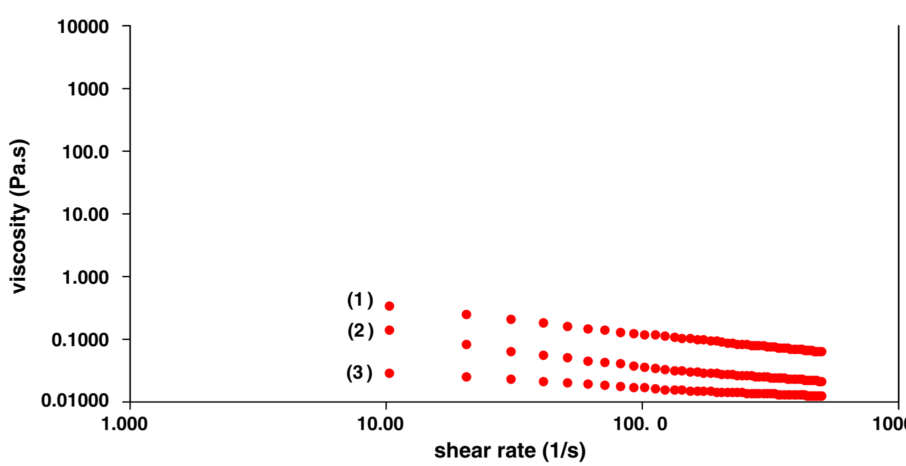

Fig. 2. Effects of extruded blend concentration (1) 11%; (7%); (5%) on the steady-shear viscosity at 70°C in logarithmic coordinates.

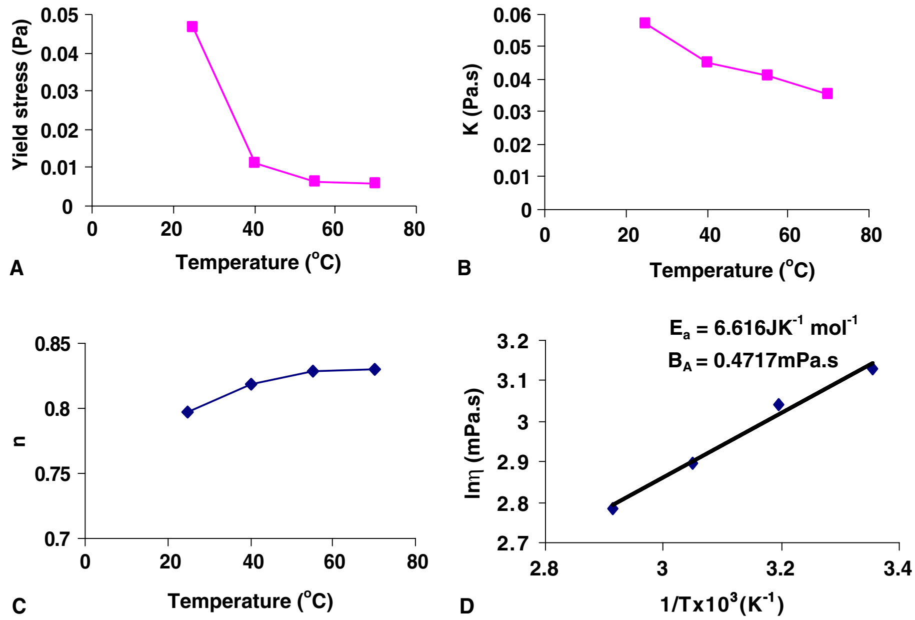

Fig. 3. Influence of temperature on σ_o (A); k (B) and n (C) of extrudate suspensions (5%); (D) shows the effect of temperature on the steady-shear viscosity of extruded blend dispersions (data at shear rate = 100 s^{-1}) and E_a calculated for a range of temperature of 25–70 °C.

($R^2 = 0.9873$). The effect of temperature is shown by the line (Lewis, 1987).

$$\ln \eta = \ln B_A + \frac{E_a}{R_g}\left(\frac{1}{T_A}\right) \tag{5}$$

where η is the viscosity, B_A is the Arrhenius constant, E_a is an activation energy constant, R_g is the gas constant, and T is absolute temperature in K. The slope and intercept of the regression of the plot ln η vs. $1/T$ were used to calculate B_A and E_a. Activation energy indicates the sensitivity of the viscosity to the temperature change.

Furthermore the forward and backward measurements, under shearing cycles, displayed slight hysteresis loops. The thixotropy behaviour (a decrease in viscosity with time) was examined at two levels of temperature, 25 and 70 °C and it was observed that, at low shear rates, the paste exhibited slight thixotropic behaviour; while, at high values, the paste behaved like an anti-thixotropic material. The thixotropic behaviour is usually attributed to the breakdown/alignment of polymer chains or segments (Al-Malalh, Azzam, & Abu-Jdayil, 2000). The experimental results showed that the degree of thixotropy increased with temperature, as indicated by the values of thixotropy of 72.50 and 90.79 Pa s at 25 and 70 °C, respectively. Table 3 shows that, according to the principle of the less the standard error, the better is the curve fit, the model that best fitted the experimental results was the H–B model. However, the curves of the Power Law models nearly coincide with H–B model.

Rheological curves obtained by the upward and downward shear rate changes in logarithmic scale (Fig. 4) show that there is a small change in the value of shear stress and this can give an indication that rheological behaviour is time-dependent. The values of σ_o, k, and n for each flow curve are shown in Table 3.

Table 3
Relative changes in rheological constants of extruded blend dispersions (5%) for the upward and downward curves at temperatures of 25 and 70 °C

Model	Temperature (°C)	Rheological parameters							
		Upward curve				Downward curve			
		σ_o (Pa)	k (Pa s)	n	SE	σ_o (Pa)	k (Pa s)	n	SE
H–B	25	4.93×10^{-2}	5.56×10^{-2}	0.826	3.92	1.29×10^{-1}	3.9×10^{-2}	0.881	1.69
P-L		NA	5.91×10^{-2}	0.817	4.34	NA	4.6×10^{-2}	0.856	1.77
Bingham		6.70×10^{-1}	1.82×10^{-2}	NA	18.36	5.47×10^{-1}	1.8×10^{-2}	NA	12.26
Casson		1.53×10^{-1}	1.47×10^{-2}	NA	6.51	9.36×10^{-2}	1.5×10^{-2}	NA	4.68
H–B	70	5.9×10^{-3}	2.60×10^{-2}	0.843	3.56	1.63×10^{-2}	1.0×10^{-2}	0.991	0.616
P-L		NA	2.24×10^{-2}	0.865	4.33	NA	1.1×10^{-2}	0.984	0.971
Bingham		2.47×10^{-1}	9.4×10^{-3}	NA	15.65	3.33×10^{-2}	9.5×10^{-3}	NA	1.081
Casson		4.01×10^{-2}	8.1×10^{-3}	NA	9.26	4.44×10^{-2}	7.5×10^{-3}	NA	26.04

σ_o, yield stress; n, flow behaviour index; k, consistency index; NA, not available; SE, standard error.

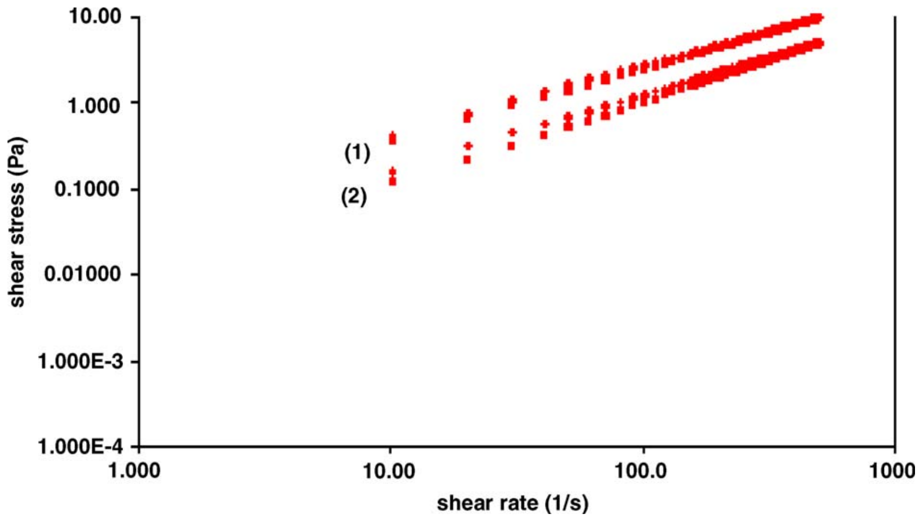

Fig. 4. Flow curves at different temperatures, 25 °C (1) and 70 °C (2), in logarithmic coordinates (concentration 5%).

4. Conclusion

From the above results, the flow behaviour characteristic is influenced by the extrudate dispersion concentration and temperature. All samples showed a non-Newtonian behaviour; i.e., the relationship between shear stress and shear rate was non-linear and this can be attributed to the presence of high molecular weight materials in the suspension. The model that best fitted the experimental data at all temperatures was the Herschel–Bulkley model which is an extension of the Power Law, by including a yield stress. From the values of the H–B model parameters, it can be seen that the yield stress and the consistency coefficient parameters increased with increasing of extrudate paste concentration. In addition, the viscosity decreased exponentially with increase of temperature. The extruded blend exhibited the well-known shear-thinning, "pseudo-plastic" behaviour with a slight shear-dependence, "thixotropy", as also shown by the hysteresis loop at 25 and 70 °C.

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