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Influence of temperature, concentration and shear rate on the rheological behavior of malay apple (*Syzygium malaccense*) juice

Influência da temperatura, concentração e taxa de deformação no comportamento reológico do suco de jambo-vermelho (Syzygium malaccense)

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Summary

The aim of this study was to evaluate the rheological behavior of malay apple, a traditional Amazonian fruit with high bioactive properties, at different temperatures and soluble solids concentrations. The experiments were carried out in a Brookfield R/S Plus rheometer with concentric cylinders geometry. Power Law, Herschel-Bulkley, Mizrahi-Berk, and Sisko rheological models were fitted to the experimental data. The malay apple juice (pulp and skin) showed a pseudoplastic behavior for all temperatures and concentrations with flow behavior indexes lower than 1. The temperature effect on the samples' apparent viscosity was analyzed by the Arrhenius equation. The activation energy increased with a decrease in the soluble solids concentration, showing that the lower the concentration, the greater the temperature influence on the apparent viscosity. The soluble solids effect was described by the exponential equation. The exponential factor increased with the temperature increasing, showing that the higher the temperature, the greater the effect of the soluble solids concentration on samples' apparent viscosity. Finally, a triparametric mathematical model combining temperature, concentration, and shear rate was proposed aiming to evaluate its effects on the samples' apparent viscosity and has accurately adjusted to the data with high correlation index R^2.

Keywords: *Rheology; Malay apple; Temperature; Concentration; Shear rate.*

Resumo

O objetivo deste estudo foi avaliar o comportamento reológico do suco de jambo-vermelho, uma tradicional fruta da região amazônica com elevadas propriedades bioativas, a diferentes temperaturas e concentrações de sólidos solúveis. Os experimentos foram realizados em um reômetro Brookfield R/S Plus, operando em geometria de cilindros concêntricos. Os modelos reológicos da Lei da Potência, Herschel-Bulkley, Mizrahi-Berk e Sisko foram utilizados para modelagem dos dados experimentais. O suco de jambo-vermelho (polpa e casca) apresentou comportamento pseudoplástico para todas as temperaturas e concentrações, com índice de comportamento de fluxo menor que 1. O efeito da temperatura na viscosidade aparente das amostras foi analisado pela equação de Arrhenius. A energia de ativação aumentou com a diminuição na concentração dos sólidos solúveis, atestando que, quanto menor a concentração, maior a influência da temperatura na viscosidade aparente. O efeito da concentração de sólidos solúveis foi descrito pela equação exponencial. O fator exponencial aumentou sob aumento da temperatura, atestando que, quanto maior for a temperatura, maior será o efeito dos sólidos solúveis na viscosidade aparente das amostras. Por fim, um modelo matemático triparamétrico, relacionando temperatura, concentração de sólidos solúveis e taxa de deformação foi proposto, visando avaliar a influência destes parâmetros na viscosidade aparente das amostras e, de forma satisfatória, ajustou-se aos dados experimentais, com elevado índice de correlação R^2.

Palavras-chave: *Reologia; Jambo-vermelho; Temperatura; Concentração; Taxa de deformação.*

1 Introduction

Native from Malaysia, malay apple *(Syzygium malaccense)*, also known as mountain apple, is a traditional fruit from the Amazon region. Oblong-shaped and with pleasant sensory qualities, malay apple is a very good source of bioactive compounds. According to Augusta et al. (2010), malay apple is rich in vitamin C and anthocyanins and, similarly to the major Myrtaceae fruits, these compounds are mainly located in the fruit's skin.

In Brazil, where the fruit is known as "jambo-vermelho", the area cultivated with malay apple, due to the ease of cultivation and appropriate climatic conditions, has experienced a considerable expansion, mainly on the north and northeast regions where the fruit is mostly consumed *in natura*. Usually, in the fruit industrial processing into other forms of products such as juices, concentrated juices, nectars, purées, syrups, jellies, and ice creams, the raw material is subjected to different industrialization processes and knowing its physicochemical properties is very important. In this respect, rheological behavior plays an essential role, not only as a quality measure, but also for designing and optimizing the processing plants (KESHANI et al., 2012; VANDRESEN et al., 2009; PELEGRINE et al., 2002).

Due to the importance of rheological properties in fluid mechanics, rheological models are used as key tools to describe the flow behavior of fluid foods. The simplest type of rheological behavior is the Newtonian one. However, most fluid foods do not display this simple behavior, requiring more complex models for their characterization. Some models have been applied to quantify how magnitudes of model parameters are affected by state variables, such as temperature, and the effect of composition (solids concentration) (TONON et al., 2009).

According to Telis-Romero et al. (1999), rheological models that express the dependence of rheological properties on temperature and on water content are a very appealing alternative to experimentation and a key tool for equipment selection. The Arrhenius equation is often used to describe the effect of temperature on apparent viscosity or on the consistency coefficient of food fluids. The effect of concentration on apparent viscosity or on the consistency coefficient of food fluids can be described either by the potential or exponential equations (STEFFE, 1996).

Therefore, the aim of this study was to determine the rheological behavior of malay apple juice prepared from fresh fruits with skin. This goal included producing and studying the juice's flow behavior as well as modeling the experimental data using rheological models, in particular the effect of temperature and soluble solids concentration on the flow. Finally, a triparametric model was proposed relating temperature, concentration, and shear rate as functions for apparent viscosity predictions. Since in industrial operations a fluid food at different concentrations is submitted to a range of shear rates and temperatures, it is essential to know how the fluid viscosity will change at these variables to appropriately design the equipment for these operations.

2 Material and methods

2.1 Acquisition and processing

Malay apple juice was extracted from a single lot of fresh malay apple fruits collected from university botanic garden (UFPA, Belém, Brazil). The fruits were chosen based on skin color (reddish color), appearance (few mechanical damages), and ripeness degree. They were washed in running water to remove surface dirt, dipped in 100 ppm sodium hypochlorite for 15 min, and washed again. Fruits were then individually cut for seed removal and processed for about 30 s in an HC 31 domestic blender (Black & Decker, Uberaba, Brazil). The juice was packed in polyethylene bags (100 g) to reduce contact with air and then quickly frozen and stored at -18 °C.

2.2 Physicochemical properties

Moisture, pH, soluble solids, total solids, and titratable acidity in the juice and in all formulations were determined according to the standard IAL methods (IAL, 2008). Moisture and total solids were determined by gravimetric method, at 105 °C, up to constant weight. Soluble solids and pH were determined in a 0767BO Abbe refractometer (Quimis, São Paulo, Brazil) and a DHMP1 pH meter (Digimed, São Paulo, Brazil) at 25 °C, respectively. Titratable acidity was determined by potentiometric titration with 0.1 N NaOH up to pH 8.1 and the results were expressed as percentage of citric acid.

2.3 Rheological measurements

The malay apple juice concentrates were diluted in distilled water, in proportions of 20, 30, and 40 g of water/100 g of sample, followed by the determination of the soluble solids concentration (°Brix).

The rheological measurements were carried out using a Brookfield R/S Plus controlled-shear-rate rheometer (Brookfield Engineering Labs, Middleboro-MA, USA) with concentric cylinder geometry (CC25). The tests were performed at 10 °C, 30 °C, 50 °C, and 70 °C. The temperature was controlled by a LAUDA 3200 thermostatic bath (Lauda, Lauda-Königshofen – Germany), properly attached to the rheometer.

The shear stress and apparent viscosity data were obtained in a controlled rate method ranging from 0 to 300 s^{-1} on the upward curve, and 300 to 0 s^{-1} on the downward curve. According to Steffe (1996), food processing involving mixing, stirring and pipe flow requires a shear rate range from 1 to 1000 s^{-1}. The total run time for each ascending and descending curve was 5 min; shear stress and apparent viscosity values were obtained every 7.5 s, resulting in 40 points. All the analyses were carried out in duplicate. The upward and downward curves virtually did not vary, indicating the absence of the thixotropic effect.

After each experimental run, a new sample of the raw material was used, avoiding changes in rheological properties.

2.4 Analyses and modeling

The Power Law (Equation 1), Herschel-Bulkley (Equation 2), Mizrahi-Berk (Equation 3), and Sisko (Equation 4) models were applied to the rheological data in order to fit the best representative model. The rheological data were obtained by the Rheo3000 software (Brookfield Engineering Labs, Middleboro-MA, USA), and the parameters were determined with Microsoft Excel 2010 (Microsoft Corporation, Redmond-WA, USA) and Origin 8.0 (OriginLab, Northampton-MA, USA).

$$\tau = K\dot{\gamma}^{n} \tag{1}$$

$$\tau = \tau_0 + K_{HB}\dot{\gamma}^{n_{HB}} \tag{2}$$

$$\tau^{0.5} = K_{0_{MB}} + K_{MB}\dot{\gamma}^{n_{MB}} \tag{3}$$

$$\tau = \mu_{\infty}\dot{\gamma} + K_S\dot{\gamma}^{n_S} \tag{4}$$

The Power Law is a classical model, highly representative for fruit juices and easy to fit, employing only two adjusting parameters. The Herschel-Bulkley model was the first one to present the yield stress parameter (τ_0), a relevant content on the study of the fluid flow. The Mizrahi-Berk model was developed as a modified Casson model (RAO, 1999). The Sisko model is an equation with three parameters which presents the viscosity parameter at infinite shear rate (μ_{∞}) (RAO, 1999). According to Nindo et al. (2007), this model has been widely used for rheological representation of fluids at high shear rates.

2.4.1 Effect of temperature, concentration, and shear rate on rheological behavior

The effect of temperature on apparent viscosity was described by the Arrhenius equation (Equation 5) (RAO, 1999) at a constant shear rate of 100 s^{-1}, where A_0 is a pre-exponential factor, E_A is the activation energy, R is the universal gas constant (0.008314 kJ/mol.K) and T is the absolute temperature.

$$\mu = A_0 \exp\left(\frac{E_A}{RT}\right) \tag{5}$$

The effect of soluble solids concentration on apparent viscosity was described by an exponential equation (Equation 6) (KHALIL et al., 1989) at a constant shear rate of 100 s^{-1}, where A_1 is the pre-exponential factor, B_1 is the concentration factor, and C is the soluble solids concentration.

$$\mu = A_1 \exp(B_1 C) \tag{6}$$

Both (Equation 5) and (Equation 6) were linearized to obtain the constants A_0, E_A, A_1 and B_1.

For engineering applications, it is very useful to obtain a single equation describing the combined effect of temperature and concentration on the fluid's apparent viscosity (STEFFE, 1996; IBARZ et al., 1992; IBARZ et al., 1996; KAYA; BELIBAGLI, 2002; QUEK et al., 2013).

The combined effect of temperature and concentration on the apparent viscosity of malay apple samples is described by combining the Arrhenius and exponential equations (Equation 7) (TELIS-ROMERO et al., 1999), where A_2, B_2 and E_A are constants to be determined.

$$\mu = A_2 \exp\left(B_2 C + \frac{E_A}{RT}\right) \tag{7}$$

Apparent viscosity can also be predicted as a function of temperature, concentration, and a shear rate range by the triparametric mathematical model below (Equation 8) (STEFFE, 1996).

$$\mu = A_3 \dot{\gamma}^{n-1} \exp\left(B_3 C + \frac{E_A}{RT}\right) \tag{8}$$

The model's parameters (A_3, n^{-1}, E_A, and B_3) were obtained by multiple linear regression from the experimental data.

2.5 Statistical analysis

The experimental data were fitted according to rheological models using the Origin 8.0 (OriginLab, Middleboro-MA, USA) software to obtain the rheological and statistical parameters (R^2 and χ^2). The values of R^2 and χ^2 were obtained to evaluate the goodness of fit to the experimental results of the rheological models.

3 Results and discussion

3.1 Physicochemical properties

Malay apple has a high moisture content (90.91g/100 g), being considered a juicy fruit. Another relevant characteristic is its low pH level (3.6), which favors its industrialization by avoiding the acidification on jelly and jams processing steps. Other characteristics were: acidity: 0.68 (g/100 g); total solids: 9.08 (g/100 g), and soluble solids: 7.8 (°Brix).

The physicochemical characteristics of malay apple fruit are in accordance with the values observed by Whistler and Elevitch (2006) when studying the physicochemical characteristics of the same fruit.

The soluble solids concentration of diluted malay apple juice samples were 5.8, 5.1, and 4.4 °Brix for 20, 30, and 40 g of water/100 g sample, respectively.

3.2 Rheological measurements and modeling

Figure 1 shows the rheograms of experimental shear stress and shear rate of malay apple juice for four concentrations at the temperature range of 10-70 °C. With no shear rates, the fruit juices are stable and only the Brownian motion is responsible for molecular agitation. According to Carreau et al. (1999), the Brownian motion allows the intermolecular attraction forces to promote the formation of flakes, gels, and networks with low molecular resistance. The application of shear rates induces the establishment of hydrodynamic forces, which quickly break the weak molecular structure initially formed, thus decreasing the apparent viscosity of the juices. The shear stress values initially grow linearly as a Newtonian fluid and tend to stability at higher shear rates. The shear stress values also showed lower magnitudes at higher temperatures and lower soluble solids concentrations, a typical behavior of pseudoplastic (non-Newtonian) fluids.

All the rheological models were satisfactorily adjusted to the experimental data and presented $R^2 > 0.90$ and χ^2 close to zero.

Due to the highest values for R^2 and the lowest values of χ^2 for four concentrations, the Mizrahi-Berk model was used as representative. This model was developed as a modified Casson model to represent the interaction of particles in a concentrated orange juice and

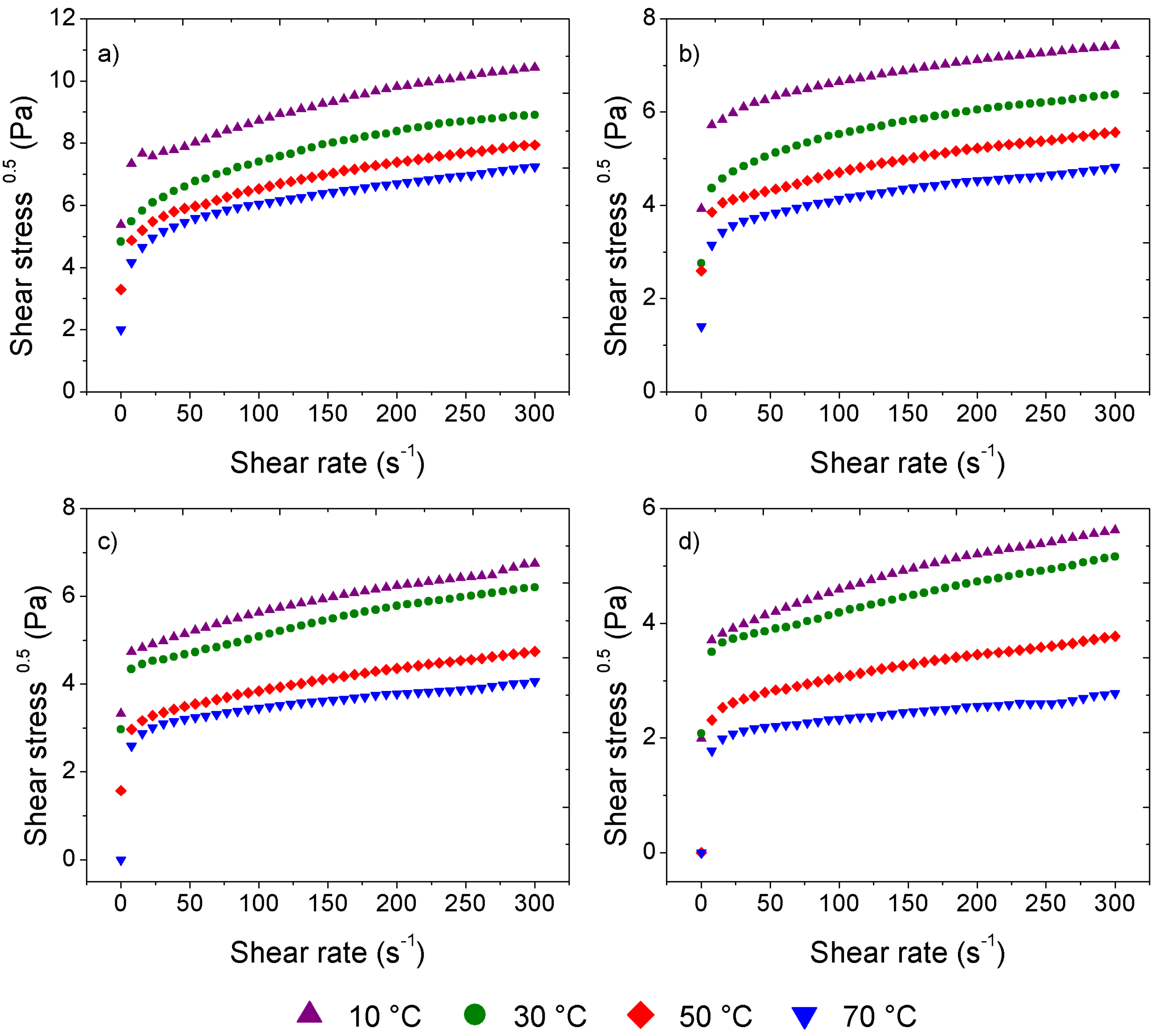

Figure 1. Flow curves of malay apple juice samples at (a) 7.8 °Brix; (b) 5.8 °Brix; (c) 5.1 °Brix and (d) 4.4 °Brix.

in other pseudoplastic solvents (MIZRAHI; BERK, 1972). The Mizrahi-Berk model parameters are shown in Table 1. This model has also been used as a representative model for carrot juices (VANDRESEN et al., 2009), pineapple and mango juices (PELEGRINE et al., 2002), and natural guava juice (FERREIRA et al., 2002).

Table 1 shows that the diluted samples presented a pseudoplastic behavior, similar to the natural samples, with flow behavior index lower than 0.5. This proves that the distilled water added to the natural sample associated to high temperatures was not enough to cause a flow transition from pseudoplastic (a non-Newtonian behavior) to Newtonian.

The consistency index did not show a regular behavior with changes in temperature and concentration. However, the yield stress values decreased as temperature and dilution increased. This suggested that malay apple juice concentrates have a network structure that requires a certain amount of force to be disrupted before flow could occur.

3.2.1 Effect of temperature and concentration on rheological behavior

There are currently several factors which may alter rheological behavior of food fluids such as temperature, concentration, and particle size (TONON et al., 2009). However, the most studied ones are temperature and soluble solids content (GUEDES et al., 2010).

A slight change in temperature may impact rheological behavior. As temperature increases, molecules thermal energy increases and molecular distances develop due to reduction of intermolecular forces hence viscosity of fluid decreases (ARSLAN, 2003). According to Schramm (2006), the temperature variation limit in a rheological test should not exceed the range of 0.1 °C. A rise in temperature increases molecular motion, thus decreasing the juice's viscosity. The constants A_0 and E_A from the Arrhenius equation, A_1 and B_1 from the exponential equation, and the relative values of temperature, concentration, and R^2 are listed in Table 2.

Table 2 shows a satisfactory goodness of fit on the Arrhenius equation for the malay apple samples, with $R^2 > 0.900$. Activation energy increased as concentration decreased. According to Steffe (1996) and Rao (1999), the activation energy indicates the influence of temperature on the apparent viscosity of fluids. According to those authors, the higher the activation energy, the higher the apparent viscosity variation in a temperature range.

Table 1. Rheological parameters of the Mizrahi-Berk model fitted to experimental data of malay apple juice samples.

C (°Brix)	*T* (°C)	K_0 (Pa.s)	K_{MB} (Pa.s^n)	n_{MB} (adimensional)	R^2	χ^2
7.8	10	5.591 ± 0.132	0.596 ± 0.075	0.366 ± 0.019	0.984	0.019
	30	4.727 ± 0.053	0.357 ± 0.024	0.437 ± 0.010	0.997	0.003
	50	3.347 ± 0.041	0.754 ± 0.027	0.316 ± 0.005	0.998	0.002
	70	2.001 ± 0.039	1.438 ± 0.033	0.225 ± 0.003	0.998	0.002
5.8	10	3.952 ± 0.037	1.050 ± 0.033	0.207 ± 0.004	0.997	0.001
	30	2.273 ± 0.022	0.916 ± 0.018	0.240 ± 0.003	0.999	0.000
	50	2.659 ± 0.056	0.567 ± 0.051	0.284 ± 0.010	0.991	0.003
	70	1.408 ± 0.026	1.189 ± 0.024	0.182 ± 0.003	0.998	0.001
5.1	10	3.429 ± 0.075	0.519 ± 0.050	0.318 ± 0.014	0.987	0.006
	30	3.130 ± 0.097	0.422 ± 0.059	0.345 ± 0.020	0.978	0.010
	50	1.633 ± 0.058	0.686 ± 0.045	0.260 ± 0.009	0.991	0.003
	70	0.005 ± 0.038	2.035 ± 0.041	0.117 ± 0.003	0.997	0.001
4.4	10	2.079 ± 0.079	0.756 ± 0.060	0.267 ± 0.011	0.987	0.006
	30	2.191 ± 0.095	0.580 ± 0.070	0.279 ± 0.017	0.973	0.009
	50	0.019 ± 0.061	1.606 ± 0.063	0.144 ± 0.005	0.991	0.004
	70	0.004 ± 0.039	1.418 ± 0.043	0.111 ± 0.004	0.992	0.002

Table 2. Parameters of the Arrhenius and exponential equations for malay apple juice samples at 100 s^{-1}.

Arrhenius equation				Exponential equation			
C (°Brix)	A_0 (Pa.s)	E_A (kJ.mol^{-1})	R^2	*T* (°C)	A_1 (mPa.s)	B_1 (°Brix^{-1})	R^2
7.8	1.03E-02	10.097 ± 0.707	0.985	10	4.82E-02	0.363 ± 0.045	0.955
5.8	1.94E-03	12.784 ± 0.184	0.999	30	5.01E-02	0.310 ± 0.035	0.963
5.1	8.97E-04	13.998 ± 2.274	0.925	50	1.64E-02	0.427 ± 0.051	0.969
4.4	8.95E-05	18.667 ± 3.522	0.900	70	7.34E-03	0.514 ± 0.098	0.900

The value of 10.097 $kJ.mol^{-1}$ found for the natural malay apple juice (7.8 °Brix) is in accordance with other studies carried out with fruits such as strawberries analyzed by Bezerra et al. (2009), peach purées by Guerrero and Alzamora (1998) and araçá pulp by Haminiuk et al. (2006). Lopes et al. (2013) studied the influence of a wide temperature range (from 20 °C to 98 °C) on the rheological behavior of Brazilian cherry pulp. They found an activation energy of 12.3 $kJ.mol^{-1}$, at 100 s^{-1}, the same reference shear rate used in the present work. According to the values obtained, temperature has a greater influence on the apparent viscosity of the most diluted sample (4.4 °Brix). Among concentrations, apparent viscosity of the natural sample (7.8 °Brix) is the least affected by temperature.

The activation energy from Arrhenius equation is obtained by plotting the logarithm of apparent viscosity versus inverse temperature. The slope multiplied by the universal gas constant gives the value of activation energy. The greater the slope, the higher the activation energy. Figure 2 shows the steeper slope obtained with the lower soluble solids concentration (4.4 °Brix) which analogously had the highest activation energy.

Similar results have been reported by Sousa et al. (2014), Quek et al. (2013) and Silva et al. (2005), who observed that activation energy increased as soluble solids of pequi pulp, soursop juice and acerola juice, respectively, decreased.

Dak et al. (2007) obtained increasing activation energy values as a consequence of lower solids content of Kesar mango juice.

Activation energy also gradually increased when Totapuri mango solids concentration decreased, as reported by Dak et al. (2006).

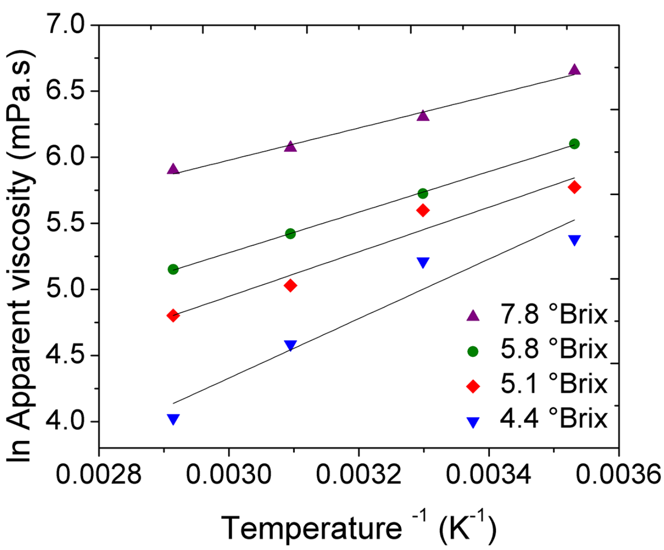

Figure 2. Temperature dependency of apparent viscosity at 100 s^{-1} obtained from the Mizrahi-Berk model.

Nevertheless, Khalil et al. (1989) examined the influence of temperature on clarified banana juice and realized that activation energy increased with a higher soluble solids concentration. The same behavior was found in studies performed with clarified orange juice (IBARZ et al., 1994) and homogenized peach juice (TORALLES et al., 2006).

In the study developed by Chin et al. (2009), the highest activation energy was obtained at an intermediate concentration. According to the authors, there are inconsistent reports about changes in activation energy with concentration. While some authors observe the highest activation energy in less concentrated products, others report the highest activation energy in line with the maximum soluble solids concentration.

According to Chin et al. (2009), activation energy decreases with the presence of suspended solid particles in fruit juices, which may be the differential matter among the aforementioned studies.

Since no studies have been found related to the rheology of malay apple juice, it was not possible to compare the activation energy values found in the present study with other researches. Nevertheless, the magnitude of the activation energy values for fruit juices, pulps and purées (QUEK et al., 2013; BEZERRA et al., 2009; GUERRERO; ALZAMORA, 1998; LOPES et al., 2013; SILVA et al., 2005; DAK et al., 2006, 2007) are in accordance with the present study.

According to Rao (1999), the soluble and insoluble solids concentrations are seen as one of the key components in identifying a rheological behavior. Soluble solids are mainly composed of carbohydrates (sugars). Carbohydrates have the ability to fix water. Carbohydrate-water interactions produce not only a special arrangement of water molecules around the solute, but also affect solute's conformation. At higher carbohydrates concentrations, the complex carbohydrate-water interaction reduces the system's free energy and, consequently, not all the water is available to hydrate the particles (BENÍTEZ et al., 2009). The effect of soluble solids concentration on apparent viscosity of fluids may be described by two equations – the potential and the exponential equations (STEFFE, 1996; RAO, 1999). In this study, an exponential equation was applied to evaluate the effect of soluble solids concentration of malay apple samples.

The exponential equation has also been used with great accuracy to assess the soluble solids concentration in pomelo juice (KESHANI et al., 2012), watermelon pulp (GUEDES et al., 2010), acerola juice (SILVA et al., 2005), and peach purée (GUERRERO; ALZAMORA, 1998).

Table 2 shows an abrupt decrease in the pre-exponential factor (A_0). On the other hand, the exponential factor (A_1) related to soluble solids concentration increases with temperature, showing that changes in soluble solids concentration, for the same pattern, affect more viscosity at high temperatures.

Figure 3 shows a steeper line at 70 °C in comparison with the other ones, showing a large disparity between the points referring to the apparent viscosity. Thus, the value of parameter A_1 is higher.

These results are in accordance with Silva et al. (2005), who have also observed a decrease in parameter A_0 and an increase in parameter A_1 as temperature increases. Guerrero and Alzamora (1997) obtained a decrease in the values of parameter A_0 with higher temperatures for banana purée, a similar effect to the one found in the present study. A similar effect was reported by Chin et al. (2009) with grapefruit juice by applying the potential equation.

However, some authors noticed a distinct behavior on the exponential equation parameters with an increase in temperature, showing a greater influence on the soluble solids concentration in low temperatures.

An increase and a decrease on parameters A_0 and A_1, respectively, were obtained with the study of the rheology of clarified orange juice by Ibarz et al. (1994), who noticed a Newtonian behavior. The authors used exponential and potential models to evaluate the influence of soluble solids on viscosity.

The behavior of exponential equation parameters with temperature increase may be due to the rheological behavior observed. Pseudoplastic fluids show an increase in the values of parameter A_1 with higher temperatures, whereas the opposite behavior was observed in parameter A_1 for Newtonian fluids. Therefore, it can be seen that there is no general behavior for A_0 and A_1 in the exponential equation as temperature increases.

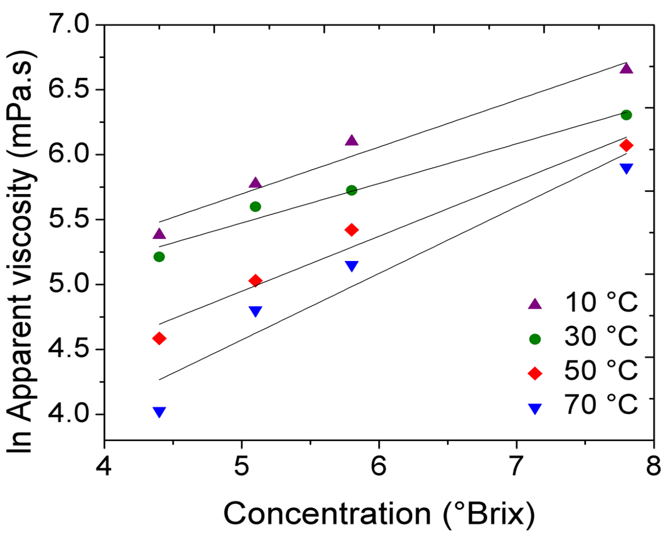

Figure 3. Concentration dependency of apparent viscosity at 100 s^{-1} obtained from the Mizrahi-Berk model.

An equation combining temperature and concentration (Equation 9) was derived from the linearized Equation 7. A multiple linear regression was accomplished to estimate the three equation parameters A_2, B_2, and E_A.

$$\mu = 0.104 \exp\left(0.408C + \frac{13.869}{RT}\right) \tag{9}$$

$R^2 = 0.943$

It should be emphasized that this equation is applicable only for concentrations within the range of 4.4 to 7.8 °Brix and temperatures between 10 °C and 70 °C.

These results show that apparent viscosity increases with higher soluble solids concentration and lower temperature. Similar results were reported by Gabsi et al. (2013) on date syrup concentrates and by Quek et al. (2013) on soursop juice concentrates.

3.2.2 Combined effect of temperature, concentration, and shear rate on rheological behavior

For a shear rate ranging from 100 to 300 s^{-1}, usually applied in industrial juice processing, an equation combining temperature, concentration, and shear rate (Equation 10) was developed by multiple linear regression.

$$\mu = 2.311\dot{\gamma}^{-0.678} \exp\left(0.409C + \frac{13.938}{RT}\right) \tag{10}$$

$R^2 = 0.878$

Due to the highly satisfactory goodness of fit, $R^2 > 0.870$, Equation 9 and Equation 10 could be appropriately applied to industrial processes involving malay apple juice.

4 Conclusion

Malay apple juice, obtained from fruits with skin, showed a pseudoplastic behavior. The Power Law, Herschel-Bulkley, and Sisko models showed a good fit to the experimental data. However, the Mizrahi-Berk model was chosen due to its higher goodness of fit. The Arrhenius and exponential equations satisfactorily represented the influence of temperature and concentration on samples' apparent viscosity, respectively. It was observed that apparent viscosity was more sensitive to changes such as increased temperature and dilution.

A triparametric mathematical model combining temperature, concentration, and shear rate was proposed in the research and satisfactorily represented the effect of the three variables on the apparent viscosity of natural and diluted malay apple juice with high R^2 coefficient, allowing its application in industrial juice processes involving malay apple fruit.

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