Rheological behavior of concentrated peach puree and its dilutions in a stationary state

Comportamento reológico em estado estacionário de purê de pêssego concentrado e suas diluições

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ABSTRACT
A rheometer equipped with a concentric cylinder system, was used to study the effects of temperature (15, 25, 40, 55 and 70°C) and concentration (10, 12, 15, 20, 25 and 30.5°Brix) on the flow behavior of peach puree. The rheograms were analyzed by the Power law, Herschel-Bulkley, Bingham and Casson models. The different sample concentrations were prepared as from a concentrated peach puree at 30.5°Brix, with absolute density of 1077.49kg/m³, pulp content of 60.90% and pH value of 3.51. All the puree concentrations showed pseudoplastic behavior at all the temperatures with yield stress, and the Herschel-Bulkley model adequately described the flow behavior. The temperature dependence was well described by the Arrhenius model. The flow activation energy (Ea) of the concentrated peach puree (30.5°Brix) was 5.556kJ.mol⁻¹ and increased with reduction in the soluble solids concentration. The exponential model was adequate to describe the effect of the puree concentration on the apparent viscosity (ηa) and on the consistency index (K). Physicochemical characterization and rheological parameters are used by the food industry to optimize the development of processes, equipment and quality control procedures for the production of pulps, nectars and fruit juices.

Keywords: Rheology, Prunus Persica (L.) Batsch, Apparent Viscosity, Activation Energy.

RESUMO
Um reômetro equipado com um sistema de cilindros concêntricos, para estudar o efeito da temperatura (15, 25, 40, 55 e 70°C) e da concentração (10, 12, 15, 20, 25 e 30.5°Brix) no comportamento reológico de purê de pêssego. Os reogramas foram analisados através dos modelos da Lei da Potência, Herschel-Bulkley, Bingham e Casson. As concentrações das amostras foram a partir de um purê de pêssego concentrado a 30,5°Brix, apresentando massa específica de 1077,49kg/m³, teor de polpa de 60,90% e pH de 3,51. As amostras de purê em todas as concentrações e temperaturas exibiram comportamento...
1 INTRODUCTION

The peach (Prunus persica (L.) Batsch) is one of the temperate climate fruits most produced worldwide. According to FAO (2021), in 2019, world production of peach and nectarine was approximately 25 million tons. The peach is one of the most appreciated fruits for its flavor and appearance, and its production is growing expressively not only “in natura” consumption but also for industrialization of jams, nectars, juices, ice creams, preserves etc. Peach puree obtained by concentrating the pulp to soluble solids contents between 30 and 32ºBrix has been commercialized nationally and internationally (Toralles & Vendruscolo, 2007; Castro et al., 2010; Mayer, Franzon, & Raseira, 2019).

Codex Alimentarius (2005) defines fruit purees for the manufacture of juices and nectars as the non-fermented but fermentable product obtained by concentrating the edible part of the whole or peeled fruit without removing the juice, but removing sufficient water to increase the Brix to at least 50% of the Brix established for the reconstituted juice of the same fruit, which, in the case of reconstituted peach juice is 10.5 ºBrix.

In general fruit and vegetable purees show pseudoplastic behavior and the Power Law model has been adopted as ideal to interpret their behavior (Rao, 1977; Massa, González, Maestro, Labanda, & Ibarz, 2010; Lopes, Mattietto, Menezes, Silva, & Pena, 2013; Diamante & Umemoto, 2015). Peach puree has been classified according to this behavior due to a complex interaction between the components of the pulp, the soluble pectin, the organic acids and the soluble solids (Rao, 1999; Haminiuk, Sierakowski, Vidal & Masson, 2006; Rojas, Leite, Cristianini, Alvim, & Augusto, 2016).
Some studies have described the flow behavior of peach puree, evaluating several conditions such as the effects of the pH value, temperature, the addition of glucose and the concentration of the soluble solids. It was shown that the fluid was non-Newtonian and independent of the time, being classified as pseudoplastic. The models that best characterized the flow of peach purees reconstituted by extrusion were shown to be the Power Law, Herschel-Bulkley and Casson models (Guerrero & Alzamora, 1998; Akdogan & Mchugh, 2000; Toralles, Luiz Vendruscolo, & Tondo Vendruscolo, 2006; Maceiras, Álvarez, & Cancela, 2007 and Massa et al., 2010).

The same behavior was found for peach pulp (Costa, 2007), peach juice (Rao et al., 2014; Rojas et al., 2016), buriti juice (Rodrigues, Bezerra, Silva, & Silva, 2016), whole murta pulp (Feitosa, Figueirêdo, Queiroz, Souza, & Silva, 2015), malay apple juice (Santos, Silva, Rodrigues, & Souza, 2016), cherry puree (Lukhmana, Kong, Kerr, & Singh, 2018), acai pulp (Costa, Arouca, Silva, & Vieira, 2018), lychee pulp (Duarte, 2018), added pineapple juice of yacon and xantane gum (Spacki, Oliveira, Mendes, Costa & Matiucci, 2020). Newtonian behavior was observed in the depectinized and clarified peach juice (Ibarz, Gonzalez, Esplugas, & Vicente, 1992).

The rheology of fruit products has been widely studied, and, in general, fruit purees and their derivatives show non-Newtonian behavior. Despite the processing operations to which they are submitted, fruits and puree like peach puree, are rich in fibers and pectic substances which provide a type of internal structure that results in this type of behavior (Massa et al., 2010). The objective of the present study was to evaluate the effects of temperature and the soluble solids concentration on the rheology of peach puree, analyzing the fitting of Power Law, Herschel Bulkley, Bingham and Casson model to rheological data. This information is important for process development, use of equipment and quality control in food industries.

2 MATERIAL AND METHODS

2.1 SAMPLE CHARACTERIZATION

The peach puree used in this work was provided by the company GOLDEN PEACH Ind e Com. de Produtos Alimenticius Ltda and was obtained from the varieties Maciel-Jade-Esmeralda. Before characterizing the sample, the amount received, about 19kg divided in 3 laminated sacks, was mixed and homogenized in a 30L jacketed vacuum vat (Groen MGF Co., USA).
The physicochemical characterization of the puree was carried out according to the analytical methodologies of the Adolfo Lutz Institute Analytical Norms (Instituto Adolfo Lutz., 2008). The pH value was determined using a model DM22 calibrated pH meter (Digimed) and the soluble solids (ºBrix) measured using a model SR400 digital refractometer (Schmidt & Haenshl). The absolute density was determined using a glass filter weight at 25°C maintained by a model MA-184 thermostatic water bath (Marconi). All the analyses were carried out in triplicate.

To determine the pulp content, the samples were centrifuged at 4500 rpm (equivalent to 3742.2g) for 15 minutes at 25°C in a Beckman model Avanti J-25 centrifuge (Vitali, 1981). A known amount of sample was homogenized with the same amount of distilled water and the supernatant was weighed. The yield, expressed as the percentage, was calculated based on the initial mass of peach puree and the mass of suspended pulp obtained after centrifugation.

The puree sample was divided into approximately 130g portions in polyethylene bags and stored in a horizontal freezer at -7 to -8°C until the moment of analysis.

Rheological characterization was carried out in sample diluted to concentrations of 10, 12, 15, 20 and 25ºBrix. For each temperature of analysis, three portions at 30.5ºBrix were removed from the freezer and maintained at room temperature until a temperature of 25°C was reached. They were then diluted with agitation to a concentration of 25ºBrix with distilled water, which was confirmed using a digital refractometer. The rheological characterization was then carried out at this concentration. In sequence the same sample was diluted to 20ºBrix and the rheological behavior characterized. This procedure was repeated throughout the sequence until reaching 10ºBrix. Hence the rheological assays were all carried out using the same sample originally at 30.5ºBrix, for each temperature.

2.2 RHEOLOGICAL CHARACTERIZATION

The rheological characterization assays were carried out using a model R/S+ SST rheometer (Brookfield Inc.) connected to a model MA-184 thermostatic water bath (Marconi) to maintain the assay temperatures: 15, 25, 40, 55 and 70°C.

The measurement systems adopted to carry out the characterization analyses in the stationary state were defined according to the concentration of the peach puree to avoid turbulence flow and errors in the voltage readings. The concentric cylinder system was used for the concentrations of 10, 12, 15, 20ºBrix and the Vane system for the 25 and 30.5ºBrix samples. The technical specifications for these measurement systems were the
following: CCT sample cup with an internal radius of 24.5mm and length of 126mm; 400mm long 40:20 Vane spindle with a radius of 200mm; 82mm long CCT-45 cylindrical spindle with a radius of 22.5mm fixed to an 84mm long rod with a radius of 3.5mm (Brookfield, 2012). The sample was kept in the reomether cup for approximately 10 minutes before start analysis, for temperature equalization. The analyses were performed in triplicate, imposing a steady shear ramp from 0 to 235 1/s followed by 235 to 0 1/s, at 25 ± 0,5°C. The time of each assay was 5 min. and 150 data of shear stress readings were collected in each assay.

The rheological behavior of the fluid was characterized by the mathematical model that best fitted the experimental data of the increasing and decreasing curves. The Ostwald-de-Waele (1), Herschel-Bulkley (2), Bingham (3) and Casson (4) mathematical models were used to fit the data.

\[
\tau = K\gamma^n \\
\tau = \tau_0 + K\gamma^n \\
\tau = \tau_0 + K\gamma \\
\tau^{0.5} = \tau_0^{0.5} + K\gamma^{0.5}
\]

Where: \( \tau \) = shear stress; \( \gamma \) = rate of deformation; \( \tau_0 \) = yield stress; \( K \) = flow consistency index; \( n \) = flow behavior index.

2.3 EFFECT OF TEMPERATURE ON THE RHEOLOGICAL PARAMETERS

The Arrhenius model was used to quantify the effect of temperature on the apparent viscosity \( \eta_a \) (Equation 5) and consistency index, \( K \) (Equation 6):

\[
\eta_a = \eta_\infty \exp\left(\frac{E_a}{RT}\right) \\
K = K_\infty \exp\left(\frac{E_a}{RT}\right)
\]

Where: \( R \) is the universal gas constant (8.314 J.mol\(^{-1}\).K\(^{-1}\)), \( T \) the temperature in Kelvin, and \( \eta_\infty \) and \( K_\infty \) are pre − exponential factors.

2.4 EFFECT OF CONCENTRATION ON THE RHEOLOGICAL PARAMETERS

The effects of concentration on the apparent viscosity (\( \eta_a \)) and consistency index (\( K \)) at 100s\(^{-1}\) were quantified by Equations 7 and 8 (Vitali & Rao, 1984):

\[
\eta_a = \eta_{a,100} \exp(B.C) \\
K = K^c \exp(B.C)
\]
The constants $\eta_{a,100}^C$, $K^C$ and $B$ were determined from the experimental data and $C$ is the soluble solids concentration in $^\circ$Brix.

The fitting of the rheological models and the statistical analyses were carried out using Microsoft Office Excel®. Correlation coefficient ($R^2$), standard deviation between repetitions, and residual standard deviation (RSD) were the statistical parameters used to evaluate the fitted models. $R^2$ values close to one-unit, low average deviation values and, according to Atala, Costa, Maciel, & Maugeri (2001), RSD values below 10% represents a satisfactory mathematical model.

3 RESULTS & DISCUSSION
3.1 CHARACTERIZATION OF THE PEACH PUREE AT 25ºC

No studies were found that reported these parameters (pH, absolute density, pulp content) considering the same concentration and temperature studied in the present work, however, Massa et al. (2010), on analyzing the physicochemical characteristics of peach puree obtained a pH value of 3.81, pulp content of 44% and soluble solids content of 21 $^\circ$Brix. Ramos & Ibarz (1998) reported a density of 1130.31 kg/m$^3$ at 25ºC for clarified peach juice at 30ºBrix, higher than the value found in the present work.

One relevant parameter is its low pH value of 3.51, favoring industrialization due to its acid characteristic. This contributes to its stability with respect to microbial development together with the conservation technology adopted. The pH encountered in the present study complies with that cited in Ordinance nº58 of August 30$^{th}$ 2016 for peach pulp which cites a minimum of 3.00 (Brasil, 2016). Several studies can be found with different fruit pulps which showed acid characteristics, such as those of malay apple, cupuacu, guava, gabiroba, jaboticaba, cherry, watermelon, uba mango and lychee (Santos, 2013; Ferreira, 2008; Oliveira, Rossi & Barros, 2011; Sato & Cunha, 2007; Lopes, 2005; Diniz, 2009; Guedes, Ramos, & Diniz, 2010; Rodrigues et al., 2016; Duarte, 2018).

The absolute density of the peach puree of 1077.49 kg/m$^3$ can be compared with that of various products: Silva, Guimarães & Gasparetto (2005) found a density of 1055.5 kg/m$^3$ for 13ºBrix acerola juice at 20ºC and Rodrigues et al. (2016) found a density of 1040.0 kg/m$^3$ at 25ºC for 4.35ºBrix buriti juice. Some higher values were also found such as 1097.4 kg/m$^3$ found by Diniz (2009) for uba mango pulp and 1149.7 kg/m$^3$ for 35ºBrix watermelon pulp at 30ºC, as found by Guedes et al. (2010).
The value for pulp content determined in the present study was 60.90%, but similar results with the same product were not found. However, some authors quantified the pulp content in other fruit pulps such as jaboticaba pulp at 21.70%, cupuaçu pulp at 44%, acerola juice at 85.32% and cherry pulp at 88.63%, presenting soluble solids contents of 13, 10, 13 and 11.67ºBrix respectively (Sato & Cunha, 2007; Ferreira, 2008; Silva, et al., 2005; Lopes, 2005).

3.2 RHEOLOGICAL CHARACTERIZATION

For all the concentrations and temperatures tested the fluid presented pseudoplastic behavior, mainly at lower temperatures and higher concentrations. This type of behavior was also observed by Guerrero & Alzamora (1998), Toralles et al. (2006), and Massa et al. (2010) for peach purees. Other authors also verified the same behavior for guava (Vitali & Rao, 1982), papaya (Ahmed & Ramaswamy, 2004) and banana (Ditchfield, Tadini, Singh, & Toledo, 2004; Ibarz, Falguera & Garvin, 2010) purees, cherimoya juice (Quek, Chin, Yusof, 2013) and noni pulp (Sousa, Queiroz, Figueirêdo, & Silva, 2017).

All the models used to describe the rheological behavior of peach puree presented high correlation coefficients and low RSD values. The Herschel Bulkley and Casson models provided the best fitting parameters for all the temperature and concentration ranges studied, with RSD values below 0.657% and $R^2$ above 99%, whereas the Bingham and Ostwald de Waele models presented values for $R^2$ varying between 90 and 98% and between 96 and 99%, respectively.

With respect to the Ostwald de Waele model at all the temperatures studied, $R^2$ values were all above 0.96 and RSD values below 10% with a variation of 0.087 to 0.360 on the rising curves. There was little variation in the flow behavior index ($n$) with temperature, although there was a decrease with increase in soluble solids concentration, confirming the non-Newtonian behavior and greater pseudoplasticity at high concentrations, since the values for “$n$” tend to move away from unity. On the other hand the consistency index (K) decreased with increase in temperature at all concentrations, corroborating the results of other researchers with various fruit products such as peach puree (Toralles et al., 2006), various concentrations of cashew juice (Assis, Tadini & Lannes, 2005), cupuacu pulp (Ferreira, Guimarães & Maia, 2008; Borges, Pires, Sampaio, & Vélez, 2017), watermelon pulp (Guedes et al., 2010), pequi pulp (Sousa, Queiroz, Figueirêdo, & Silva, 2017).
Figueirêdo, & Lemos, 2014), malay apple pulp (Santos et al, 2016), and buriti juice (Rodrigues et al., 2016).

It is observed that the increase in shear rate caused a decrease in the slope of the flow curves and in apparent viscosity values, characterizing the pseudoplasticity. Apparent viscosity values of fitted models also decreased with temperature increasing. According to Pelegrine (1999) since the majority of fruit pulps is composed by solids dispersed in a liquid medium, an increase in temperature causes a decrease in the viscosity of the liquid phase, increasing the movement of the suspended particles and consequently decreasing the viscosity of the pulp.

The Herschel-Bulkley model is widely used to characterize rheological behavior of food products, since it embraces the Newton, Bingham and Ostwald-de-Waele models. Results showed that for the peach puree, representative values for the yield stress ($\tau_0$) were detected for all the concentrations and temperatures used. This yield stress is equivalent to the minimum shear stress required for the fluid to start flowing, i.e., to behave as a viscous liquid, this being related to the internal structure of the fluid under study. On the other hand, stress values below this limit impedes flow and the material behaves as an elastic solid (Tabilo-Munizaga & Barbosa-Cánovas, 2005; Bayod, Månsson, Innings, Bergenståhl, & Tornberg, 2007). The presence of yield stress is a typical characteristic of multiphasic materials (Sun & Gunasekaran, 2009) such as peach puree, formed of pulp which is an insoluble matter (consisting of fruit tissue cells, cell walls etc.) dispersed in serum (solution composed of soluble polysaccharides, sugars, salts and acids) (Rojas et al., 2016; Augusto, Ibarz, & Cristianini, 2012a; Augusto, Ibarz, & Cristianini, 2012b).

The values obtained for the yield stress ($\tau_0$) varied from 3.779 to 125.661 Pa, the flow behavior index ($n$) from 0.312 to 0.571 and the consistency index (K) from 0.896 to 85.032 (Pa.s^n) within the temperature and concentration ranges studied. The sensibility of these parameters according to temperature were observed by the decreasing of their values.

The same model was also used and adopted with the best regression fits by Maceiras et al. (2007) and Massa et al. (2010) in studies with peach puree and by Augusto, Falguera, Cristianini, & Ibarz, (2011) in studies with peach juice added with fibers. It also describes adequately the rheological behavior of others fruit products such as jaboticaba pulp (Sato & Cunha, 2007; 2009), acai pulp (Tonon, Alexandre, Hubinger, & Cunha,
2009), acerola pulp (Pereira, Resende & Giarola, 2014) and cherry puree (Lukhmana et al., 2018).

Table 01 compares the values obtained for yield stress values ($\tau_0$), flow behavior index (n) and consistency index (K) of the peach puree at 30.5°Brix and 25°C, with results of other studies available in the literature for fruit products.

<table>
<thead>
<tr>
<th>Product</th>
<th>T (°C)</th>
<th>$\tau_0$(Pa)</th>
<th>K (Pa.s$^n$)</th>
<th>n</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peach puree (30.5°Brix)</td>
<td>25</td>
<td>117.92</td>
<td>75.08</td>
<td>0.34</td>
<td>Present work</td>
</tr>
<tr>
<td>Peach puree (21°Brix)</td>
<td>25</td>
<td>25.3</td>
<td>11.3</td>
<td>0.32</td>
<td>Massa et al. (2010)</td>
</tr>
<tr>
<td>Blueberry puree (10-25°Brix)</td>
<td>25-60</td>
<td>27.45</td>
<td>0.07-7.2</td>
<td>0.64-0.49</td>
<td>Nindo et al. (2007)</td>
</tr>
<tr>
<td>Banana puree (22°Brix)</td>
<td>25</td>
<td>1.9</td>
<td>17.2</td>
<td>0.23</td>
<td>Ibarz et al. (2010)</td>
</tr>
<tr>
<td>Purê de banana (22.1°Brix)</td>
<td>30</td>
<td>81.04</td>
<td>4.67</td>
<td>0.44</td>
<td>Ditchfield et al. (2004)</td>
</tr>
<tr>
<td>Acerola pulp (13.5°Brix)</td>
<td>20</td>
<td>0.37</td>
<td>13.93</td>
<td>0.36</td>
<td>Pereira et al. (2014)</td>
</tr>
<tr>
<td>Gabiroba and guava pulps</td>
<td>25</td>
<td>0.07-26.82</td>
<td>6.05-48.32</td>
<td>0.63-0.80</td>
<td>Oliveira et al. (2011)</td>
</tr>
<tr>
<td>(14.5-50°Brix)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pequi pulp (12°Brix)</td>
<td>25</td>
<td>80.82</td>
<td>135.74</td>
<td>0.66</td>
<td>Sousa et al. (2014)</td>
</tr>
<tr>
<td>Umbu pulp (25°Brix)</td>
<td>30</td>
<td>8.06</td>
<td>37.74</td>
<td>0.29</td>
<td>Pereira et al. (2008)</td>
</tr>
<tr>
<td>Cherry pulp (11.67°Brix)</td>
<td>20</td>
<td>1.67</td>
<td>0.16</td>
<td>0.63</td>
<td>Lopes (2005)</td>
</tr>
<tr>
<td>Noni pulp (30°Brix)</td>
<td>25</td>
<td>14.35</td>
<td>88.43</td>
<td>0.18</td>
<td>Sousa et al. (2017)</td>
</tr>
<tr>
<td>Acerola and mango pulp</td>
<td>25</td>
<td>3.96-4.52</td>
<td>0.17-0.14</td>
<td>0.66-0.71</td>
<td>Silva et al. (2012)</td>
</tr>
<tr>
<td>Malay apple pulp (7.8°Brix)</td>
<td>30</td>
<td>22.28</td>
<td>2.82</td>
<td>0.53</td>
<td>Santos (2013)</td>
</tr>
</tbody>
</table>

The peach puree is characterized by high consistency, since high values of $\tau_0$ (117.92Pa) and K (75.08 Pa.s$^n$) were fitted at 25°C, when compared to the other fruit products. Table 01 also shows that yield stress values closest to the presented results were those for banana pulp ($\tau_0$ = 81.04Pa) and pequi pulp ($\tau_0$ = 80.82Pa), whereas higher values of consistency index were presented for noni pulp (K = 88.43 Pa.s$^n$) and pequi pulp (K = 135.74 Pa.s$^n$), and lower values for guava pulp (K = 48.32 Pa.s$^n$).

For the Bingham model, an increase in temperature (from 15 to 70°C) caused a decrease either in yield stress as in the consistency index, whereas viscosity values were decreased. Sato & Cunha (2007) also verified a considerable reduction in both these parameters for jaboticaba pulp at temperatures of from 5 to 85°C, Oliveira et al. (2011) in gabiroba and guava pulps at 20 to 35°C, and Reticena (2015) in pure passion fruit pulp at 10 to 60°C. It is also observed that all the values fitted for yield stress in all concentrations and temperatures were higher than those predicted by the Herschel-Bulkley model. The opposite behavior was noticed for the consistency index.

Consistency index fitted to Casson model also decreased with increase in temperature and little variation were verified in the yield stress values. On the other hand, notable increasing were observed in consistency index and yield stress values with
increasing in the soluble solids content. Similar behavior was shown by Nindo, Tang, Powers, & Takhar (2007) for blueberry puree (25 - 60°C at 10 - 25°Brix), acerola juice (5 - 85°C at 13°Brix) (Silva et al., 2005) and acerola, cashew and mango pulps (8 - 45°C) (Silva et al., 2012). It is noticed that the yield stress values (2.193 – 16.131 Pa) and the consistency indexes (0.107 – 0.724 Pa.s) were considerably smaller than those fitted to the Herschel-Bulkley model (yield stress values of 3.779 – 125.661Pa; and consistency indexes of 0.896 – 85.032 Pa.s

### 3.2.1 Effect of temperature on the apparent viscosity and consistency index

Using a non-linear fit of the apparent viscosity data (\( \eta_a \)) from the Ostwald de Waele model to an Arrhenius equation, the activation energy and fitting parameter \( \eta_\infty \) values were determined for the peach puree at temperatures of from 15°C to 70°C. These parameters regard to apparent viscosity at a rate of 100s\(^{-1}\) are presented in Table 02, are an important information for industrial processing operations (Steffe, 1996).

<table>
<thead>
<tr>
<th>*SS (°Brix)</th>
<th>( \eta_\infty ) (Pa.s)</th>
<th>( E_a ) (KJ.mol(^{-1}))</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.005±0,0003</td>
<td>9.259±0,156</td>
<td>0.961</td>
</tr>
<tr>
<td>12</td>
<td>0.005±0,0003</td>
<td>10.300±0,141</td>
<td>0.983</td>
</tr>
<tr>
<td>15</td>
<td>0.007±0,0004</td>
<td>10.587±0,143</td>
<td>0.996</td>
</tr>
<tr>
<td>20</td>
<td>0.012±0,0010</td>
<td>11.266±0,204</td>
<td>0.992</td>
</tr>
<tr>
<td>25</td>
<td>0.202±0,0215</td>
<td>6.336±0,270</td>
<td>0.959</td>
</tr>
<tr>
<td>30,5</td>
<td>0.561±0,1679</td>
<td>5.556±0,720</td>
<td>0.923</td>
</tr>
</tbody>
</table>

*Soluble solids

The Arrhenius equation fitted satisfactorily for the different concentrations of peach pulp, as proved by the high values for \( R^2 \) of between 0.923 and 0.996.

The activation energy (\( E_a \)) values adjusted for the peach puree at concentrations between 10 and 30.5°Brix were from 5.556 to 11.266 KJ.mol\(^{-1}\). These values were in agreement with other studies carried out with similar fruits using temperature ranges and concentrations similar to those used in the present study, such as noni pulp (4.647 KJ.g\(^{-1}\).mol\(^{-1}\) for the whole pulp and 164.950 KJ.g\(^{-1}\).mol\(^{-1}\) 30°Brix pulp) (Sousa et al., 2017), blueberry puree (10.7 – 21.7 KJ.mol\(^{-1}\) for 10 - 25°Brix) (Nindo et al., 2007), depectinized apple juice (5.3 – 14.2 Kcal.g\(^{-1}\).mol\(^{-1}\) for 15 – 75°Brix), orange juice (4.2 – 5.4 Kcal.g\(^{-1}\).mol\(^{-1}\) for 30 - 44°Brix) and peach puree (1.7 Kcal.g\(^{-1}\).mol\(^{-1}\) at 11.7°Brix) (Saravacos, 1970). According to Saravacos (1970), the activation energy
decreases significantly in the presence of suspended particles in fruit purees and juices. It can also be seen that the values for the constant \( \eta_\infty \) are low and increase with increase in the soluble solids concentration. The same behavior was found by Guedes et al. (2010) in a study on the effect of temperature and concentration on the physical properties of watermelon pulp.

Note that the higher the soluble solids concentration the smaller the effect of temperature on the rheological properties of studied fluid, as observed through reduction of the activation energy values \( (E_a) \). Thus, the activation energy was greater for smaller concentrations, indicating the sensitivity of the viscosity of the puree to the temperatures studied. According to Steffe (1996), high values for the activation energy indicate a rapid change in the viscosity with temperature.

According to the values obtained, the temperature exerted a greater influence on the apparent viscosity of the sample at 20°Brix. On the other hand, the apparent viscosity of the concentrated peach puree at 30.5°Brix was the least affected by temperature changes. Guerrero & Alzamora (1998) observed values from 13 to 15 KJ.mol\(^{-1}\); Toralles et al. (2006) values between 10.4 and 13.6 KJ.mol\(^{-1}\) for peach purees, and Ibarz et al. (1992) values from 4.63 to 13.29 Kcal.mol\(^{-1}\) for peach juice, showing similar behavior when compared to present study. Values for the activation energy increased with increase in concentration in these studies, whilst in the present study higher soluble solids concentrations showed smaller values for the activation energy, similar to those presented for malay apple pulp (Santos, 2013), watermelon pulp (Guedes et al., 2010) and pequi pulp (Sousa et al., 2014).

The same behavior was found by Oliveira et al. (2011) for gabiroba and guava pulps, by Feitosa et al. (2015) for whole myrtle pulp, by Ferreira et al. (2008) for whole cupuacu pulp, and by Lopes et al. (2013) and Sato & Cunha (2007) studying the rheological behaviors of cherry and jaboticaba pulps, respectively.

After fitting the consistency index \( (K) \) to the Arrhenius equation, the values for activation energy and the fitting parameter \( K_\infty \) were determined for the peach puree at temperatures of from 15 to 70°C, as described in Table 03.

Table 03. Arrhenius parameters or the effect of temperature on consistency index \( (K) \) at a shear rate of 100s\(^{-1}\) of peach puree, valid for the range of 15 to 70°C.

<table>
<thead>
<tr>
<th>°S (°Brix)</th>
<th>( K_\infty ) (Pa.s)</th>
<th>( E_a ) (KJ.mol(^{-1}))</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.651±0.113</td>
<td>5.383±0.386</td>
<td>0.818</td>
</tr>
<tr>
<td>12</td>
<td>0.660±0.263</td>
<td>6.476±0.953</td>
<td>0.820</td>
</tr>
<tr>
<td>15</td>
<td>1.078±0.189</td>
<td>6.617±0.412</td>
<td>0.957</td>
</tr>
</tbody>
</table>
Quite good representativeness of the Arrhenius equation for the experimental data obtained for the peach pulp is verified through $R^2$ above 0.642. A comparison of the parameters obtained by fitting the apparent viscosity data to those obtained using the consistency index shows that the values for activation energy obtained based on the apparent viscosity (Table 02) were higher than those obtained based on the consistency index (Table 03). The behavior of activation energy (Ea) values agreed with apparent viscosity behavior, with a greater influence of temperature at 20ºC, and lower influence in the concentrations of 25 and 30.5ºBrix. On the other hand, the values for the constant ($K_\infty$) suffered an abrupt increase with the increase in soluble solids concentration.

### 3.2.2 Effect of concentration on the apparent viscosity and consistency index

The concentration, size, and shape of the particles in suspension have a strong influence on the viscosity of fruit pulps and purees (Saravacos, 1970). Tables 04 and 05 show the values obtained for apparent viscosity and consistency index for the peach puree at concentrations varying from 10 to 30.5ºBrix and temperatures of from 15 to 70ºC and their effects on the shear rate of 100s$^{-1}$.

**Table 04.** Exponential parameters for the effect of concentration (°Brix) on apparent viscosity at a shear rate of 100s$^{-1}$ of peach puree, valid for the range of 10 to 30.5 °Brix.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$\eta_{100}$ (Pa.s)</th>
<th>B (°Brix)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.054±0.0002</td>
<td>0.156±0.0003</td>
<td>0.996</td>
</tr>
<tr>
<td>25</td>
<td>0.049±0.0004</td>
<td>0.156±0.0002</td>
<td>0.996</td>
</tr>
<tr>
<td>40</td>
<td>0.039±0.0005</td>
<td>0.160±0.0005</td>
<td>0.997</td>
</tr>
<tr>
<td>55</td>
<td>0.028±0.0005</td>
<td>0.166±0.0018</td>
<td>0.992</td>
</tr>
<tr>
<td>70</td>
<td>0.023±0.0003</td>
<td>0.170±0.0014</td>
<td>0.997</td>
</tr>
</tbody>
</table>

**Table 05.** Exponential parameters for the effect of concentration (°Brix) on consistency index at a shear rate of 100s$^{-1}$ of peach puree, valid for the range of 10 to 30.5 °Brix.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$k_\infty$ (Pa.s)</th>
<th>B (°Brix)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1.216±0.0183</td>
<td>0.167±0.0020</td>
<td>0.994</td>
</tr>
<tr>
<td>25</td>
<td>1.232±0.0236</td>
<td>0.164±0.0006</td>
<td>0.994</td>
</tr>
<tr>
<td>40</td>
<td>1.098±0.0111</td>
<td>0.167±0.0006</td>
<td>0.997</td>
</tr>
<tr>
<td>55</td>
<td>0.859±0.0267</td>
<td>0.172±0.0030</td>
<td>0.989</td>
</tr>
<tr>
<td>70</td>
<td>0.705±0.0303</td>
<td>0.177±0.0015</td>
<td>0.996</td>
</tr>
</tbody>
</table>
The non-linear fit of Equations 07 (\(\eta_a = \eta_{a,100}^C e^{(B.C)}\)) and 08 (\(K = k^C e^{(B.C)}\)) represented satisfactorily behaviors of apparent viscosity and consistency index, verified by high values of \(R^2\) values, above 0.99. Parameter B tended to remain constant with the variation in temperature, whereas for \(\eta_{a,100}^C = 0.023 - 0.054\)Pa.s and \(k^C = 0.705 - 1.232\)Pa.s, the values decreased with temperature, indicating that the effect of concentration was greater at lower temperatures. The values adjusted for \(\eta_{a,100}^C\) were lower than the values reported by Toralles et al. (2006) for peach puree, \(\eta_{a,100} = 0.044 - 0.071\)Pa.s, whereas for \(K = 0.32 - 0.78\)Pa.s, the values were higher. The same was found for the consistency coefficient in relation to the data obtained by Guerrero & Alzamora (1998), \(K = 0.39 - 0.57\)Pa.s for peach puree para and Ibarz et al. (2010) found values of \(\eta_a = 0.29 - 0.47\)Pa.s and of \(K = 1.07 - 10.00\) Pa.s for banana puree, both higher than the results found in the present study.

4 CONCLUSIONS

The peach puree sample at 30.5 Brix and its dilutions (10, 12, 15, 20, 25 Brix) presented pseudoplastic characteristics, with high values for the consistency indexes and flow behavior indexes less than one unit, and also a lack of linearity between the shear rates versus shear stress was observed. Despite the high values of correlation coefficients of Ostwald-de-Waele and Bingham models, the Herschel Bulkley and Casson models described the flow behavior of the peach puree samples better in the range of concentration studied, showing that the fluid requires significant yield stress to start flowing.

The apparent viscosity decreased with increase in temperature for all the sample and conditions studied, and the higher the soluble solids concentration of the sample, the greater the pseudoplasticity, confirming the fact that the physicochemical characteristics of fruit products can influence their rheological behavior.

The Arrhenius equation and the Exponential equation represented the effects of temperature and soluble solids concentration, respectively, in the samples studied, with elevated correlation indexes. As expected, and reported in the literature for other types of fruit purees and pulps, the activation energy decreased with increase in the soluble solids concentration.
REFERENCES


