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Effect of whey protein concentrate on texture of fat-free desserts: sensory and instrumental measurements

Efeito do concentrado protéico de soro na textura de sobremesas lácteas sem gordura: medidas sensorial e instrumental

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Abstract

It is important to understand how changes in the product formulation can modify its characteristics. Thus, the objective of this study was to investigate the effect of whey protein concentrate (WPC) on the texture of fat-free dairy desserts. The correlation between instrumental and sensory measurements was also investigated. Four formulations were prepared with different WPC concentrations (0, 1.5, 3.0, and 4.5 wt. (%)) and were evaluated using the texture profile analysis (TPA) and rheology. Thickness was evaluated by nine trained panelists. Formulations containing WPC showed higher firmness, elasticity, chewiness, and gumminess and clearly differed from the control as indicated by principal component analysis (PCA). Flow behavior was characterized as time-dependent and pseudoplastic. Formulation with 4.5% WPC at 10 °C showed the highest thixotropic behavior. Experimental data were fitted to Herschel-Bulkley model. The addition of WPC contributed to the texture of the fat-free dairy dessert. The yield stress, apparent viscosity, and perceived thickness in the dairy desserts increased with WPC concentration. The presence of WPC promotes the formation of a stronger gel structure as a result of protein-protein interactions. The correlation between instrumental parameters and thickness provided practical results for food industries.

Keywords: fat-free dairy dessert; whey protein concentrate; sensory analysis; rheological properties; texture profile analysis.

Resumo

É importante entender como as mudanças na formulação de um alimento podem afetar suas características. Sendo assim, o objetivo deste trabalho foi estudar o efeito da adição de concentrado protéico de soro (CPS) na textura de sobremesas lácteas tipo flan sem gordura. A correlação entre as medidas instrumentais e sensoriais também foi investigada. Quatro formulações foram desenvolvidas com diferentes concentrações de CPS (0, 1,5, 3,0 e 4,5% em massa) e avaliadas instrumentalmente por meio de análise de perfil de textura (TPA) e reologia. A consistência foi avaliada por nove julgadores treinados. As formulações adicionadas de CPS apresentaram maior firmeza, elasticidade, mastigabilidade e gomosidade em relação à amostra controle, como indicado na análise de componentes principais. O comportamento ao escoamento das sobremesas lácteas foi caracterizado como tempo-dependente e pseudoplástico. A formulação contendo 4,5% de CPS a 10 °C apresentou maior comportamento tixotrópico. Os dados experimentais foram ajustados ao modelo de Herschel-Bulkley. A adição de CPS contribuiu para a textura das sobremesas lácteas sem gordura. Os valores de tensão inicial, viscosidade aparente e consistência das sobremesas lácteas aumentaram com a concentração de CPS. A presença de CPS promoveu uma estrutura de gel mais forte como resultado das interações proteína-proteína. A correlação entre os parâmetros instrumentais e a consistência sensorial forneceu informações práticas para a indústria de alimentos.

Palavras-chave: sobremesa láctea sem gordura; concentrado protéico de soro; análise sensorial; propriedades reológicas; análise de perfil de textura.

1 Introduction

In recent decades there has been increasing interest in the development of low-fat or fat-free products. People are motivated to consume low-fat dairy products in order to ensure overall good health and reduce the risk of several types of diseases, such as obesity, hypertension, cerebral apoplexy, and coronary heart diseases (SANDOVAL-CASTILLA et al., 2004; YOO et al., 2007). The formulation of these foods constitutes a great challenge for the food industry since fat has multiple properties which affect food texture, appearance, flavor and aroma (GONZÁLEZ-TOMÁS et al., 2008). Texture is an important parameter in formulated foods containing structuring agents such as proteins and polysaccharides. González-Tomás et al. (2008) studied the influence of two types

of thickeners, starch and k-carrageenan, on the rheological and sensory properties of low-fat dairy desserts and observed differences in the orally perceived thickness.

The use of whey protein concentrate (WPC) in dairy products would be an alternative approach for maintaining the sensory properties by making them a more attractive product to the consumer. WPC has been considered an interesting fat-substitute ingredient due to its functional and technological properties, as well as its nutritional appeal since it contains high concentrations of bioactive proteins. Whey protein functionality is associated to its composition and degree of denaturation (LIZARRAGA et al., 2006). Proteins are composed of uniform and spherical particles allowing the sliding

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of one particle over another offering the sense of creaminess. (PINHEIRO; PENNA, 2004). β-lactoglobulin is the major protein in whey, and it is considered the main gel-forming agent due to the presence of free sulfhydryl groups in the molecule. WPC has been used as a fat substitute in various foods such as yogurt (AZIZNIA et al., 2008; SANDOVAL-CASTILLA et al., 2004; LOBATO-CALLEROS et al., 2004), cheese (LOBATO-CALLEROS et al., 2007), and sausage (YOO et al., 2007). Sandoval-Castilla et al. (2004) studied the addition of three commercial fat replacers consisting of whey protein concentrate (WPC), microparticulated whey protein (MWP), and modified tapioca starch (MTS), alone and combined. These authors reported that yogurt with WPC and blends of WPC and MWP have textural characteristics similar to those of full-fat yogurt.

Food texture comprises mechanical properties, tactile sensations, and also visual and audible stimuli. The texture properties are most accurately measured by sensory analysis techniques which use trained judges to detect and evaluate specific texture attributes. In order to reduce expenses and variability of tests with individuals, different instruments have been developed to simulate sensory perceptions (FOEGEDING, 2007). Recently, several studies on the rheological characterization of dairy desserts have been conducted (TORRES; TÁRREGA; COSTELL, 2010; DOUBLIER; DURAND, 2008; GONZÁLEZ-TOMÁS et al., 2008; DE WIJK; PRINZ; JANSSEN, 2006; GONZÁLEZ-TOMÁS; COSTELL, 2006), most with the purpose of relating sensory texture measurements and rheological data obtained by fluid flow and viscoelasticity characterization. Instrumental Texture Profile Analysis (TPA) has been effectively applied to many kinds of foods (KIM et al., 2009; LASSOUED et al., 2008; LEE et al., 1999; PONS; FISZMAN, 1996).

Based on rheological measurements, the product formulation can be modified to produce a more attractive food. Accordingly, the objective of the present study was to evaluate the effect of whey protein concentrate in fat-free dairy desserts by means of instrumental and sensory methods. (TPA) and rheological measurements were carried out and the results were correlated with sensory data obtained from a trained panel.

2 Material and methods

2.1 Dairy Dessert elaboration

The samples were produced with soluble WPC (33% protein) (Gemacom, Juiz de Fora, Brazil), k-carrageenan (Griffith, Mogi das Cruzes, Brazil), commercial skimmed-milk powder (Itambé, Sete Lagoas, Brazil), corn starch (Unilever, Mogi Guaçu, Brazil), sucrose, and a vanila flavour (Duas Rodas, Jaraguá do Sul, Brazil).

Four dairy desserts (Control, F1, F2, and F3) were formulated with different concentrations of WPC (0, 1.5, 3.0, and 4.5 wt. %), respectively. The concentrations of sugar (12.0 wt. %), skimmed-milk powder (10.0 wt. %), corn starch (5.0 wt. %), vanilla flavor (2.5 wt. %), and k-carrageenan (0.02 wt. %) were kept constant. The solids were mixed with water in a dry pan and the mixture was maintained under agitation in a water bath at 40 °C for 2 minutes. Subsequently, the temperature was increased to 90 ± 2 °C for 15 minutes for pasteurization. The temperature was then reduced to 40 °C, vanilla flavor was added, and the mixing continued for another 2 minutes. The samples were put in plastic cups, covered to avoid drying, and stored under refrigeration (4 ± 1 °C) until instrumental and sensory analysis. Three batches were prepared for each dessert.

2.2 Texture profile analysis

TPA was carried out using the universal testing machine (Instron – Series 3367, United Stated, 2005) with a 0.05 N load cell. Compression measurements were conducted at 10 °C using a probe 50 mm diameter to apply 20% constant strain to a sample of 50 mm diameter and 40 mm height (PONS; FISZMAN, 1996). The test speed was 2 mm/s with two penetration cycles. The force exerted on the sample was automatically recorded, and the parameters of firmness (N), chewiness (J), gumminess (N), cohesiveness (dimensionless), adhesiveness (N.s), and elasticity (mm) were automatically evaluated from the force (N) × time (s) curves generated during the test by the Blue Hill 2.0 software (Instron, United States, 2005). A fresh sample was used for each measurement. Three batches of each composition were prepared, and at least five measurements were performed on each batch.

2.3 Rheological analysis

Rheological analyses were performed with a rotational rheometer (Brookfield, R/S plus SST 2000 model) and a coaxial cylinder sensor CC14 (inner cylinder radius of 7 and 21 mm in length and outer cylinder radius of 7.59 mm). The measurements were taken under constant temperatures of 10 and 25 °C, selected as representative of common dairy dessert temperature for consumption and oral temperature developed during consumption of the semi-solids foods, respectively (TÁRREGA; DURAN; COSTELL, 2005; ENGELEN et al., 2003). A fresh sample was loaded for each rheological measurement. Three batches of each composition were prepared, and at least two measurements were performed on each batch.

Thixotropic characterization was carried out under constant shear rate of 10/s for a period of 10 minutes at temperatures of 10 and 25 °C. The shear measurements were taken at 6- second intervals for 10 minutes totalizing 100 points in each test.

The model of Figone and Shoemaker (Equation 1) was used to describe the time dependent flow properties of the samples:

$$\tau(t) = \tau_e + (\tau_0 - \tau_e).e^{-k_i.t} \tag{1}$$

where $\tau(t)$ is the shear stress (Pa) at a given time (s), τ_e is the shear stress at equilibrium (Pa), τ_0 is the initial shear stress (Pa), and K_i (/s) is the constant of the structural destruction kinetic.

Rheological measurements were carried out in a controlled stress mode. Flow curves were obtained by progressively increasing the shear rate (γ) to 200/s for 120 seconds, followed by a decreasing over the same time period. The average shear

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Table 1. Values of instrumental texture parameters for fat-free dairy desserts with different concentrations (0, 1.5, 3.0, and 4.5 wt. (%)) of WPC (Control, F1, F2, and F3, respectively).

Formulations	Firmness (N)	Elasticity (mm)	Cohesiveness (dimensionless)	Chewiness (J)	Gumminess (N)
Control	1.18 ± 0.03	4.51 ± 0.35	0.90 ± 0.07	5.48 ± 1.24	0.76 ± 0.15
F1	1.33 ± 0.03	4.90 ± 0.29	0.91 ± 0.02	6.51 ± 0.27	0.89 ± 0.04
F2	1.49 ± 0.05	4.95 ± 0.14	0.91 ± 0.01	7.31 ± 0.26	0.99 ± 0.02
F3	1.48 ± 0.06	4.91 ± 0.14	0.88 ± 0.01	6.55 ± 0.51	0.89 ± 0.09
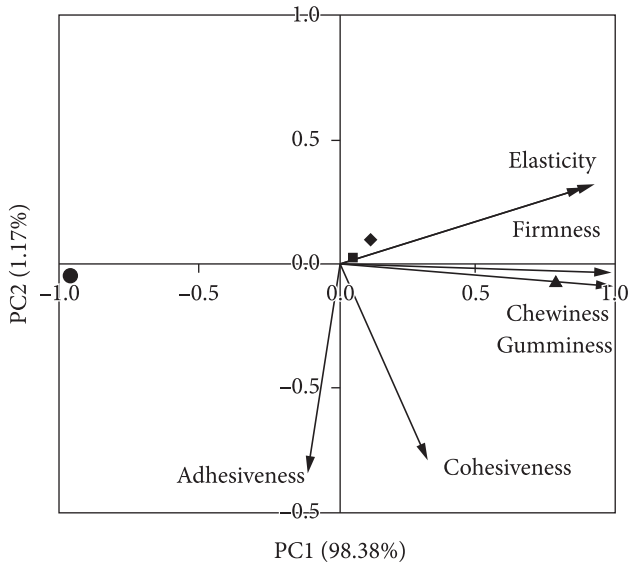
Figure 1. Principal Component Analysis of instrumental texture parameters for fat-free dairy desserts with different concentrations (0, 1.5, 3.0, and 4.5 wt. (%)) of WPC (• Control, ■ F1, ▲F2, and ♦F3, respectively).

Figure 2. Variation of shear stress over time for fat-free dairy desserts with different concentrations (0, 1.5, 3.0, and 4.5 wt. (%)) of WPC (Control, F1, F2, and F3, respectively) at 10/s for at temperatures of 10 and 25 °C.

stress for each shear rate was evaluated. Before each experiment, a constant shear rate of 100/s was applied for 3 minutes for thixotropy breakdown.
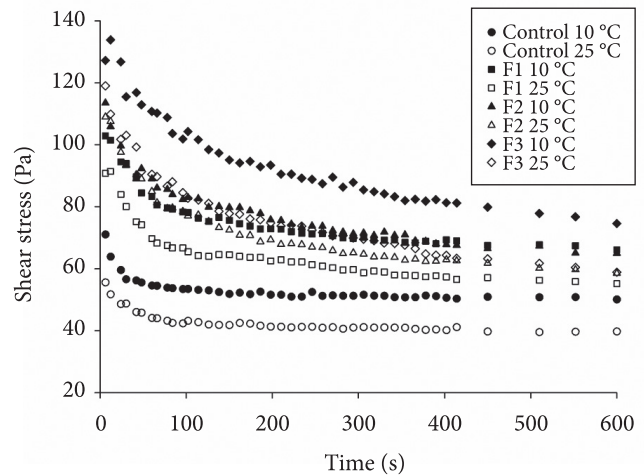
The Hershel-Bulkley (Equation 2) model was adjusted to the rheological data:

$$\tau = \tau_0 + K\dot{\gamma}^n \qquad (2)$$

where: τ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (/s), τ_0 is the yield stress (Pa), K is the consistency index (Pa.s^n), and n is the flow behavior index (dimensionless). Apparent viscosity at 10/s was obtained from the equation of Herschel-Bulkley.

2.4 Sensory evaluation

The sensory characterization of the formulations was carried out by means of Quantitative Descriptive Analysis (QDA) by a trained panel (STONE et al., 1974; STONE; SIDEL, 1998). Thickness was one of the eight attributes assessed by the trained panel according to ISO 11036:1994 (INTERNATIONAL…, 1994). Thickness evaluation was conducted in a standardized room (ISO 8589) (INTERNATIONAL…, 1988), with white fluorescent lighting. The panelists were selected based on their ability to discriminate the samples and their repeatability.

The sample thickness was evaluated by nine-member trained panel using a 9-cm non-structured linear scale anchored at the extremities with terms that express intensity (very and little). Chilled samples (10 °C) were presented to the panelists at room temperature (25 °C). In the final evaluation, the four samples were coded with three digit numbers and shown simultaneously in three sessions. Mineral water was used to rinse the mouth between consecutive samples.

2.5 Statistical analysis

One-factor (sample) ANOVA was applied to the instrumental data. Principal Component Analysis (PCA) with varimax rotation was applied to the correlation matrix of the average values of instrumental texture parameters.

The experimental data of thixotropy and flow behavior were fitted to Figone & Shoemaker and Hershel-Bulkley models, respectively. The quality of the model fit was verified according to the significance level (p) and determination coefficient (R^2).

Sensory data was analyzed by ANOVA and regression analysis. The correlation between the instrumental and sensory texture measurements was determined using the Pearson correlation coefficient (r). All analyses were performed using the SAS statistical software version 9.1 (SAS Institute, Inc., Cary, NC, USA).

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Table 2. Values of rheological parameters of Figoni–Shoemaker equation for fat-free dairy desserts with different concentrations (0, 1.5, 3.0, and 4.5 wt. (%)) of WPC (Control, F1, F2, and F3, respectively).

T (°C)	Formulation	τ_0 (Pa)	τ_e (Pa)	$(\tau_0 - \tau_e)$ (Pa)	K_i (/s)	R^2
10	Control	70.99 ± 0.81	51.25 ± 0.09	19.74 ± 0.72	0.030 ± 0.002	0.930
	F1	102.45 ± 0.82	67.98 ± 0.21	34.47 ± 0.61	0.012 ± 0.000	0.967
	F2	103.50 ± 0.95	65.85 ± 0.48	37.65 ± 0.47	0.007 ± 0.000	0.956
	F3	127.63 ± 0.82	74.96 ± 0.58	52.67 ± 0.26	0.006 ± 0.000	0.981
25	Control	54.63 ± 0.54	40.41 ± 0.09	14.22 ± 0.45	0.018 ± 0.001	0.930
	F1	90.08 ± 1.03	57.27 ± 0.25	32.81 ± 0.78	0.012 ± 0.001	0.946
	F2	106.41 ± 0.91	60.68 ± 0.31	45.72 ± 0.60	0.009 ± 0.000	0.975
	F3	109.73 ± 1.01	60.29 ± 0.58	49.44 ± 0.43	0.006 ± 0.000	0.970

τ_0: initial stress; τ_e: shear stress at equilibrium; $(\tau_0 - \tau_e)$: break-down structure during shearing; K_i: structural degradation kinetic constant. Control (without WPC addition), F1 (1.5% of WPC), F2 (3.0% of WPC) and F3 (4.5% of WPC).

2.6 Ethics committee

This project was analyzed and approved by the Scientific Graduate Committee of the Department of Food Technology – Federal University of Viçosa, process nº. 50717257515/2009, complying as outlined, with the necessary requirements for its publication.

3 Results and discussion

3.1 Texture Profile Analysis (TPA)

Average values and associated uncertainties of texture parameters of the samples are presented in Table 1. The results of the ANOVA indicated that the addition of WPC affected the parameters of firmness, elasticity, chewiness, and gumminess ($p < 0.10$).

The Principal Component Analysis (PCA) of average texture parameters showed that the first two components accounted for 99.55% of the total variability of the data, with the first component explaining 98.38%. Figure 1 shows the correlation of instrumental texture parameters and the spatial arrangement of samples in relation to the two principal components. The first principal component (PC1) was strongly associated with elasticity, firmness, chewiness, and gumminess, and it clearly separated the control sample from the others. These results indicated that the addition of WPC to the formulations contributed to enhance textural properties, except for adhesiveness and cohesiveness, which is attributed to its high water retention capacity and gelling properties. This is in agreement with the results presented by Antunes, Motta and Antunes (2003), who reported that β-lactoglobulin is the main gelling agent due to the presence of free sulfhydryl groups. Formulations supplemented with WPC showed greater elasticity. This parameter is strongly related to the formation of intermolecular disulfide bonds (SHIMADA; CHEFTEL, 1989). The second principal component (PC2) is associated with the parameters adhesiveness (r = –0.84) and cohesiveness (r = –0.78). PC2 explains only 1.17% of total data variation indicating that there was no difference between the samples in terms of adhesiveness and cohesiveness.
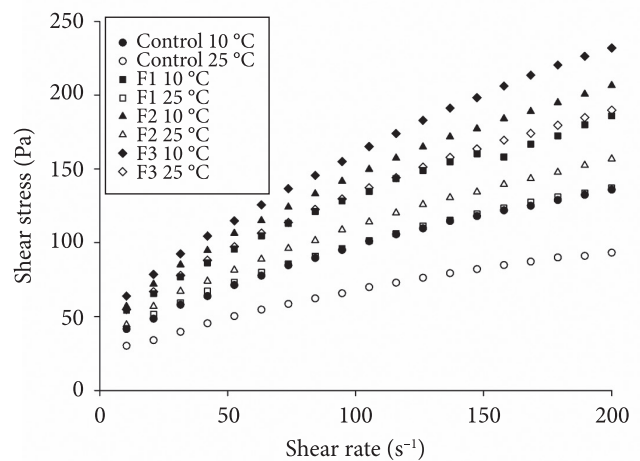

Figure 3. Experimental results of the shear rate sweep tests for fat-free dairy desserts with different concentrations (0, 1.5, 3.0, and 4.5 wt. (%)) of WPC (Control, F1, F2, and F3, respectively) at temperatures of 10 and 25 °C.

3.2 Rheological analysis

Thixotropic characterization

The thixograms obtained for the shear stress versus time, at constant shear rate of 10/s, showed time dependency at both temperatures of 10 and 25 °C (Figure 2). Shear stress decayed with time, and this behavior is similar to that found by González-Tomás and Costell (2006) and Tárrega and Costell (2007) in commercial dairy desserts. It is observed that thixotropy presented two stages. In the first stage, there was a significant shear stress decay due to sample disintegration. In the second stage, the decay was slower due to the change of particle orientation caused by deformation. This behavior was found by several authors (RAMOS; IBARS, 1998; ABU-JDAYIL, 2003; BASU; SHIVHARE; RAGHAVAN, 2007) during the thixotropic characterization of orange juice and quince pulp, and pineapple jelly, and concentrated yogurt, respectively.

The model of Figone & Shoemaker was satisfactorily fit to the experimental data with values of R^2 greater than 0.930 (Table 2). It is observed that the amount of structure degradation during shear stress ($\tau_0 - \tau_e$) increases when the

Table 3. Steady-state parameters of Herschel–Bulkley equation for fat-free dairy desserts with different concentrations (0, 1.5, 3.0, and 4.5 wt. (%)) of WPC (Control, F1, F2, and F3, respectively).

T (°C)	Formulation	τ_0 (Pa)	K (Pa × s^n)	n	R^2	η_{10} (Pa × s)
10	Control	18.41 ± 2.85	5.22 ± 0.83	0.59 ± 0.03	0.998	3.87
	F1	23.21 ± 5.59	7.28 ± 1.65	0.58 ± 0.04	0.997	5.12
	F2	24.66 ± 2.35	7.58 ± 0.66	0.60 ± 0.01	0.999	5.49
	F3	35.23 ± 2.36	5.59 ± 0.52	0.67 ± 0.02	0.999	6.16
25	Control	14.24 ± 2.32	3.41 ± 0.66	0.59 ± 0.03	0.998	2.78
	F1	20.44 ± 1.64	5.15 ± 0.48	0.59 ± 0.02	0.999	4.05
	F2	20.22 ± 1.77	6.03 ± 0.51	0.59 ± 0.01	0.999	4.36
	F3	28.04 ± 2.05	5.70 ± 0.52	0.63 ± 0.02	0.999	5.25

τ_0: yield stress, K: consistency index, n: flow behavior index, η_{10}: apparent viscosity under shear rate of 10/s.

concentration of WPC increases. According to Corrêa et al. (2005), elevating the thixotropy tends to increase the product shelf-life because it presents higher viscosity during storage, which complicates component separation. This is due to the greater energy required to disrupt the structure responsible for the time dependent behavior. The structure-degradation kinetic constant (K_i) decreased as WPC concentration increased for both temperatures. In other words, the control sample reached equilibrium faster suggesting that the increase in WPC concentration forms a stronger gel structure as a result of strong protein-protein interactions, and consequently the rate of gel structure degradation is greater.

Fluid flow behavior characterization

Figure 3 shows the flow curves of the four formulations studied at 10 and 25 °C. All samples showed non-Newtonian shear-thinning flow with an apparent yield stress. This behavior is in accordance with that observed by other authors in similar products (WISCHMANN; NORSKER; ADLER-NISSEN, 2002; TÁRREGA; COSTELL, 2007).

The Herschel-Bulkley model presented good fit showing greater values for the determination coefficient in the studied temperatures (R^2 > 0.997). The samples were clearly pseudoplastic showing flow behavior indices (n) in the range of 0.58 to 0.67 (Table 3). According to Table 3, for a given temperature the yield stress values increased with the increase in WPC concentration. The yield stress represents the magnitude of plasticity and indicates the resistance of dairy desserts to permanent deformation (KEALY, 2006). Therefore, the structural resistance to flow tends to rise as the WPC concentration increases suggesting an increasing of internal structural stiffness.

Apparent viscosity under shear rate of 10/s was evaluated from the equation of Herschel-Bulkley. According to Shama and Sherman (1973), this apparent viscosity was selected as a potential practical index of sensory viscosity since it is suggested that the physical stimulus of sensory viscosity varies with flow characteristics, and for more viscous food, these stimuli appear to be related to the shear stress developed at a constant shear rate of 10/s. It is observed that apparent viscosity increased as WPC concentration increased for both temperatures.

Thickness = 0.04 + 1.90 * WPC
R^2 = 91.47%
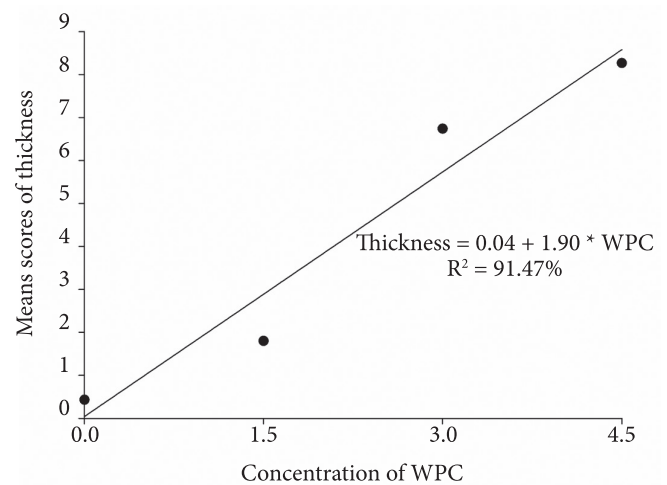
Figure 4. Sensory evaluation of thickness for fat-free dairy desserts with different concentrations of WPC.

3.3 Sensory analysis

The results obtained from the ANOVA with two sources of variation (sample and panelist) and sample versus panelist interaction showed significant differences ($p < 0.05$) in the thickness of samples.

The formulations F1, F2, F3, and control, showed mean scores of 1.8, 6.7, 8.3, and 0.43, respectively, for the thickness attribute. The control formulation showed minimal thickness while the sample F3, with 4.5% WPC, presented the highest intensity value for this attribute. It is observed that there is an increase in thickness with the increase in WPC indicating its efficiency in enhancing texture (Figure 4).

3.4 Relationship between instrumental and sensory data

The assessments of thickness, obtained by the trained taste panel, TPA (measuring firmness, chewiness, gumminess, cohesiveness, adhesiveness, and elasticity) and rheological properties (measuring flow curve parameters and thixotropy) were used for determining the correlation between instrumental and sensory measurements using the Pearson analysis.

Considering the thixotropic parameters, structure breakdown during shearing ($\tau_0 - \tau_e$) showed significant

correlation with thickness, according to the trained panel, at both temperatures (r = 0.87 at 10 °C and r = 0.91 at 25 °C). Higher values of this parameter result in a more solid-like behavior of the product resulting in more consistent sample. The structure-degradation kinetic constant (K_t) did not significantly correlate (p > 0.20) with oral thickness at 10 °C, but it showed significant negative correlation (r = –0.90) at 25 °C.

Oral thickness was also correlated to yield stress (τ_0) (r = 0.85 at 10 °C and r = 0.81 at 25 °C) and apparent viscosity at 10/s (r = 0.87 for both temperatures). According to Van Vliet (2002), the thickness of a product is related to the yield stress, which is the force required to start flow. It is expected that this measurement is similar to that observed by the panelist when evaluating thickness of food products. The correlation between oral thickness and η_{10} corroborates the proposal of Shama and Sherman (1973). These authors proposed that the apparent viscosity values under a stress rate of 10/s can result in an oral thickness index for semi-solid products. When evaluating commercial dairy desserts, Tárrega and Costel (2007) also found good correlation (p ≤ 0.14) between oral thickness and yield stress (τ_0) and apparent viscosity at 10/s and 25 °C. The flow behavior index (n) was not correlated (p > 0.21) with oral thickness at the two studied temperatures. The consistency index (K) at 25 °C correlated positively (r = 0.80) with the sensory texture attribute. These results suggest that rheological analysis at 25 °C provide parameters which better correlate with thickness perception. According to Engelen et al. (2003), 25 °C is the oral temperature developed during the consumption of the dairy desserts at 10 °C.

The correlation between the perceived thickness and the instrumental texture parameters was also determined. the oral thickness of dairy desserts showed significant correlation (r = 0.92) with instrumental firmness values. This result corroborates those found by Saint-Eve et al. (2009) investigating the effect of reducing salt and fat content on composition, texture, and sensory properties of flavoured model dairy products. These authors reported high correlation (r = 0.97) between firmness perception and firmness TPA parameters. The parameters of elasticity, cohesiveness, gumminess, and chewiness did not significantly correlate with this sensory property (p > 0.32). The non-correlation of these parameters can be attributed to differences between the chewing process and instrumental methodology used. The temperature during samples evaluation may have been a limiting factor since the tests were conducted at refrigeration temperature of samples while the oral temperature developed during the consumption of the dairy desserts is 25 °C. However, many authors describe the instrumental texture analysis (TPA) at refrigeration temperature (LOBATO, 2006; RICHTER, 2006; HUANG et al., 2007).

4 Conclusion

The formulations supplemented with WPC showed greater elasticity, firmness, chewiness, and gumminess compared to the control sample thus contributing to the texture of the fat-free dairy desserts. All formulations presented pseudoplastic behavior, yield stress, and thixotropy. The addition of WPC led to an increase in yield stress, thixotropy, apparent viscosity at the shear rate of 10/s, and perceived thickness in fat-free dairy desserts. The formulation with 4.5% WPC had the strongest gel structure, which is the result of more protein-protein interactions.

Several instrumental parameters including TPA firmness, yield stress τ_0, thixotropic parameters ($\tau_0 - \tau_e$), and K_t, and apparent viscosity η_{10} showed good correlation with oral thickness, especially at 25 °C. Therfore, these instrumental parameters can replace the sensory evaluation of texture, which is rarely used in the food industry due to cost and time required to train a sensory panel.

The textural relationships between the trained panelist, TPA, and rheometry are based on the physico-chemical nature of the products. Rheological properties and instrumental texture of the fat-free desserts were affected by WPC content leading to significant differences in the orally perceived thickness.

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