Viscosity decay of hydrocolloids under oral conditions

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13 Abstract

14 The aim of this study was to understand the contribution of hydrocolloids to oral structure
15 breakdown of starch-based systems in relation to mouthfeel sensations. For this, carrot purees were
16 prepared using corn starch and a different second thickener (λ -carrageenan,
17 carboxymethylcellulose (CMC), xanthan gum, or an extra amount of starch). The viscosity decay of
18 purees under *in vitro* oral conditions was measured (starch pasting cell adapted to a rheometer)
19 when shearing at a constant shear rate in the presence of artificial saliva. Sensory properties of
20 purees were described using the Flash Profile technique by a group of 13 panellists. Oral viscosity
21 decay of systems was modelled using a second order structural kinetic equation that included three
22 parameters: initial viscosity, rate of breakdown, and viscosity at equilibrium. Although they had the
23 same initial viscosity, the structural breakdown of the purees in oral conditions varied, depending
24 on the second thickener used. The structure of purees containing xanthan and λ -carrageenan were
25 more resistant under oral conditions exhibiting a slow and smaller breakdown. In contrast, purees
26 containing only starch showed a rapid and large decay because of the complete structure
27 breakdown by amylase. For puree containing CMC, there was also a rapid decrease, but smaller than
28 starch, indicating that part of the structure remained after digestion. Texture sensations freely
29 described by assessors varied according to two main sensory dimensions, that were clearly related
30 to the structural breakdown parameters. As expected, the dimension of thickness (from watery and
31 liquid to thick and viscous) separated base purees from thickened purees and was related to the
32 initial viscosity. The smoothness dimension (from rough and lumpy to the smooth and creamy) was
33 related to the viscosity at equilibrium indicating that after the oral digestion, the characteristics of
34 the remaining structure can explain differences in complex attributes of semisolid systems such as
35 smoothness and creaminess.

36

37 **Keywords:** oral digestion, thickener, texture, hydrocolloids, viscosity decay, texture sensations

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39

40 1. Introduction

41 Starch is usually included in the formulation of semisolid foods (purees, sauces, dairy desserts,
42 custards, soups, and puddings) as a thickener, because it is naturally available, relatively cheap, and
43 does not impart flavours at a concentration below 5% (Saha & Bhattacharya, 2010). Starch granules,
44 when heated above their gelatinisation point and in excess of water, lose their internal order,
45 absorbing water and increasing the viscosity of the system (BeMiller, 2018; Heyman, De Vos,
46 Depypere, Van der Meeren, & Dewettinck, 2014). Starch is frequently combined with other
47 thickeners that give added properties like emulsification, stabilisation, as fat replacers, or coating
48 agents (Li & Nie, 2016; Saha & Bhattacharya, 2010). The most popular non-starch thickeners in the
49 food industry are hydrocolloids from natural sources like carrageenan (seaweed origin), xanthan,
50 gum (microorganism origins), locus bean gum (seed origin), guar gum (seed origin), and cellulose
51 derivatives; imparting viscosity through gelation and polymer entanglement (Heyman et al., 2014;
52 Nussinovitch, 1997; Piculell, 2006). These hydrocolloids have a different composition and structure
53 (different branching structure, flexibility, molecular weight, and / or ionic charges) that create a
54 wide range of different rheological behaviours (BeMiller, 2018), but they all change the rheology of
55 the system by providing viscosity when dispersed in water (Saha & Bhattacharya, 2010).

56 Many studies have characterised the rheological behaviour of thickeners in water or in food
57 matrices, as the interaction with other food components dictates their molecular assembly (Ai et
58 al., 2015). Furthermore, the food industry has always been interested in relating thickeners'
59 rheological behaviour with sensory perception. Thus, shear force correlation with sensory
60 perception of a thickened food products has been studied. Researchers first postulated that
61 thickness perception, and the rheologically measured viscosity were correlated when
62 measurements took place at rates about 10 s^{-1} (Cutler, Morres, & Taylor, 1983; Shama & Sherman,
63 1973). More recently, authors found that there was a good correlation between thickened solutions'
64 rheology results and mouthfeel perception at 50 s^{-1} (He, Hort, & Wolf, 2016). However, Sharma et
65 al. (2017) found that for shear rates between 10 and 50 s^{-1} , a shear rate of 10 s^{-1} correlated better
66 with the sensory appreciation, when measuring thickened carrots purees. Ross et al. (2019) found
67 that different shear forces related to different sensory attributes. At 10 s^{-1} there was a correlation
68 with oral cohesiveness perception, while at 50 s^{-1} with oral propulsion effort, and at 100 s^{-1} with
69 perceived stickiness and oral residue. These studies show that there is not one shear rate that
70 correlated with perception; bringing to the light the importance of the dynamic nature of the oral
71 processing.

72 In the mouth, there are more variables than shear rates that affect the continuous changes of
73 rheological behaviour in semisolids foods. Heat, saliva, and enzymes are also contributing factors to
74 the continuous changes in mechanical properties. Previously reported, semisolid foods containing
75 starch, once mixed with saliva, become thinner (Heinzerling, Smit, & Dransfield, 2008), this is caused
76 by the action of the α -amylase, that hydrolyses the long-chain starch structure (Warren, Zhang,
77 Waltzer, Gidley, & Dhital, 2015). However, is not possible to measure the viscosity constantly *in vivo*.
78 From one side, it is very difficult to assess viscosity values in online processes and techniques such
79 as doppler-based Ultrasound Velocity Profiling are needed (Takeda, 1991). From the other side,
80 there are no rheological probes that fit the oral cavity whilst performing normal food oral
81 processing.

82 Previous studies have attempted to overcome the difficulty of measuring viscosity changes in
83 the mouth. One asked participants to spit out the mouth content at different times (de Wijk,
84 Janssen, & Prinz, 2011; Prinz, Janssen, & de Wijk, 2007), however as the human saliva changes its
85 rheological properties within minutes (Stokes & Davies, 2007) this makes the measurement difficult,
86 having many participants, furthermore, these samples easily spoil, microbiologically. Other authors
87 have measured changes in products under *in vitro* conditions. For example, Prinz et al., 2007, built
88 an apparatus that mimicked oral conditions, including shear, temperature, dilution, and α -amylase
89 excretion was built; however, although samples could be taken and measured aside, to record
90 rheological changes on-line was not possible. Previous to that, other authors developed what they
91 called a “structure breakdown cell”, a custom-built device with four coils that was attached to a
92 rheometer to measure viscosity changes in starch-based products to assess the functional
93 ingredients release (Sanz & Luyten, 2006) and to relate it with creaminess perception (Jellema,
94 Janssen, Terpstra, de Wijk, & Smilde, 2005). However, the change in viscosity, because of the saliva
95 action, was never modelled, hindering the understanding of the parameters that influence viscosity
96 breakdown behaviour.

97 At present, clearly, saliva affects viscosity in starch-based products. However, the loss of
98 viscosity not only entails a perceptual thickness change, it also affects the structure in which other
99 food components are imbibed, along with other complex sensation changes. To relate viscosity
100 changes to sensory perception, quantitative descriptive analysis (QDA®) has been used (de Wijk,
101 Prinz, & Janssen, 2006; He et al., 2016; Ross, Tyler, Borgognone, & Eriksen, 2019). In QDA® testing
102 the trained assessors evaluate the sensations according to the reference samples that contain the
103 stimulus responsible for the sensation pre-established by the researcher. However, when the
104 research focuses on understanding stimuli responsible for complex sensations, trained panellists are

not the best option because, in this case, the stimuli are not known. Therefore, allowing assessors to evaluate samples using their own descriptors may overcome this difficulty. Free choice profile and Flash Profile are alternative sensory techniques to QDA®, where each subject quantifies the perceived qualities of products using his or her own individual list of attributes and criteria (Oreskovich et al. 1991; Heymann 1994). Both techniques have proved useful for describing and quantifying sensory differences among a wide range of foods like dairy beverages (Arancibia, Costell, & Bayarri, 2011), biscuits (Tarancón, Sanz, Fiszman, & Tárrega, 2014), honey (Price, Tang, El Kadri, & Gkatzionis, 2019), tomato sauce (Bendini et al., 2017), and persimmon purees (Hernández-Carrión, Varela, Hernando, Fiszman, & Quiles, 2015) among many others.

All things considered, this study aimed to understand how different hydrocolloids influence oral structure breakdown of starch-based systems, and how this is related to mouthfeel sensations. Therefore, this research measures and models viscosity decay using oral conditions parameters for puree systems prepared with different thickeners and determines how different breakage patterns affect mouthfeel perception.

2. Materials and methods

2.1. Puree samples composition

Ingredients for puree samples preparation included frozen carrots, frozen onions (Hacendado, Navarra, Spain), vegetable broth (Hacendado, Guipuzcua, Spain), sunflower oil (Hacendado, Sevilla, Spain), table salt, and spring water (Cortes, Spain). Four different thickeners were used: λ -carrageenan (Satiagum™, Cargill Texturizing Solutions SL, Barcelona, Spain), xanthan gum (Satiaxane™ U, Cargill Texturizing Solutions SL, Barcelona, Spain), sodium carboxymethyl cellulose (CMC, Akzo Nobel Chemicals, Amersfoort, The Netherlands), and corn starch (C*Tex 06205 Cargill Texturizing Solutions SL, Barcelona, Spain Spain).

Composition of the base puree was: carrots (42.25%), onions (9.22%), vegetable broth (39.95%), oil (2.3%), corn starch (1%), water (5%), and salt (0.28%).

Four extra-thickened purees (ET-purees) were prepared with this same composition plus thickeners: λ -carrageenan (1.2%), xanthan gum (0.25%), sodium carboxymethyl cellulose (0.3%), and corn starch (1%). The amount of water varied (3.5 - 5%) according to the variation of the thickener.

The amounts of the second thickener correspond to those that produced ET-purees with the same viscosity (similar apparent viscosity at 10 s⁻¹ and 37 °C). They were established according to a

137 preliminary characterisation and comparison of the flow behaviour of a set of samples with a
138 different amount of each hydrocolloid (Table 1).

139

140 2.2. Puree samples preparation

141 Puree samples were prepared in 1.2 Kg batches using a kitchen robot (Thermomix, Vorwerk
142 Spain, M.S.L., Madrid, Spain). As to the puree preparation, the corresponding amount of thickener
143 was dissolved in 50 ml of vegetable stock under stirring for 1 hour. For better visualisation, Figure 1
144 shows the puree sample preparation flow chart.

145 The oil and onion were put in the vessel and cooked for 4 minutes at 100 °C. The carrot,
146 vegetable broth, and salt were added and cooked for 15 minutes at 100 °C with low speed mixing
147 subsequently the ingredients were blended for 2 minutes, at 80 °C, to a puree. Finally, the pre-
148 dissolved thickeners were added and stirred for 10 minutes, at 80 °C. Once prepared, puree was
149 transferred from the cooking vessel to two plastic containers (600 g) and stored at ambient
150 temperature for 30 minutes, and then refrigerated (4 °C) for 24 hours. Two batches of each puree
151 sample were prepared.

152 [FIGURE 1 HERE]

153

154 2.3. Composition and preparation of artificial saliva

155 The artificial saliva was prepared based on the methodology and composition (ionic
156 composition and pH) described by (Minekus et al., 2014), and contained sodium chloride (1.126 g L⁻¹
157 ¹), potassium phosphate (0.504 g L⁻¹), sodium bicarbonate (1.142 g L⁻¹), magnesium chloride
158 hexahydrate (0.03 g L⁻¹), ammonium carbonate (0.006 g L⁻¹), calcium chloride dihydrate (0.221 g L⁻¹
159 ¹), and 3 g L⁻¹ of mucin (porcine gastric mucine type II, Sigma Aldrich); 8.7 g L⁻¹ of α -amylase (A317,
160 type VI-B from porcine pancreas, Sigma Aldrich) was added 10 minutes prior to using the artificial
161 saliva. A new preparation of artificial saliva was made every test day.

162

163 2.4. Rheological properties of puree samples.

164 Samples were poured into a cylindrical sensor and were covered with plastic film for 5 minutes
165 before starting the test. Flow curves of the puree samples (preliminary set and the five study
166 samples) were obtained at 37 °C by recording shear stress values when shearing of samples
167 increased linearly from 1 to 200 s⁻¹, without preshearing the samples. A viscometer (HAAKE VT 550
168 viscometer) using a concentric cylinder sensor (MV3), monitored by a Rheowin Pro software
169 (version 2.93, Haake) was used. Data from the curve were fitted to the Ostwald-de Waele model (σ

170 = $k\dot{\gamma}^n$) where, σ is the shear stress (Pa), k is the consistency index (Pa.sⁿ), $\dot{\gamma}$ is the shear rate (s⁻¹), and
171 n is flow index (dimensionless). For each batch of puree sample, three replicates were measured.

172

173 2.5. Oral viscosity decay (*in vitro* oral digestion)

174 Changes in viscosity values during *in vitro* oral digestion were registered using a starch pasting
175 cell, adapted to a controlled stress rheometer (AR-G2, TA Instruments, Crawley, England) with a
176 Peltier concentric cylinder system to control the temperature. Twenty grams of puree were added
177 to the starch pasting cup, was covered with plastic film and was rested for three minutes to achieve
178 the measurement temperature (37 °C). Then, right before starting the test, 2 mL of artificial saliva
179 were added to the cell with a pipette. Immediately, viscosity was recorded while shearing (10 s⁻¹) at
180 37 °C for 120 s using a continuous ramp. Data were recorded with TA analysis software instruments.
181 For each batch of puree sample, three replicates were measured. To differentiate dilution and
182 hydrolysis effects caused by saliva, the same procedure was followed by adding distilled water
183 instead of saliva.

184 To model the viscosity breakdown, the structural kinetic model proposed by Nguyen et al.,
185 1998, (Nguyen, Jensen, & Kristensen, 1998) to characterise viscosity decay of thixotropic samples
186 under constant shear, was used. Here, viscosity data under oral conditions (constant shear and
187 saliva) was fitted into the second order structural equation (equation 1);

$$\frac{\eta_0 - \eta_e}{\eta - \eta_e} = Kt + 1 \quad (1)$$

188 where η is the viscosity at a given time and t is time in seconds. The parameters of the equation
189 were the initial apparent viscosity (η_0 , Pa.s), the equilibrium apparent viscosity (η_e , Pa.s), and the
190 rate of structure breakdown (K). Rate of viscosity drop (k), η_0 , and η_e were determined for each
191 replicate based on equation 1.

192

193 2.6. Sensory evaluation of purees

194 Sensory characterisation of the purees' texture was performed using the Flash Profile method.
195 Thirteen assessors with previous experience in sensory analysis (trained in the evaluation of other
196 food categories) attended two sessions. The first session was used to generate the individual
197 vocabulary of each assessor to describe the textural sensations perceived when eating puree
198 samples. For that, each panellist received six pairs of purees (different combinations of the five study
199 samples). For each pair of samples, assessors were asked to describe the differences and similarities
200 in texture. According to the descriptors used, an individual list of attributes was obtained for each

201 assessor. In the second session, the puree samples were evaluated. Each assessor received his / her
202 score card to evaluate their own attributes. The five samples were presented simultaneously, and
203 each assessor was asked to rank the sample (from low to high intensity) according to each attribute.
204 Ties were allowed.

205 All the assessments were conducted in sensory booths, designed following ISO 8589
206 (International Organization for Standardization [ISO], 2007). Spring water was available for rinsing
207 between samples, but this was not enforced. This procedure has been approved by the Ethical
208 Committee of CSIC (ethics references 018/2019)

209

210 2.7. Data analysis

211 ANOVAs were used to study the variation in apparent viscosity values at 10 s^{-1} among puree
212 samples and in the values of the structural breakdown parameters (η_0 , K , and η_e). Tukey's test post-
213 hoc was used to determine the significant ($p < 0.05$) differences among samples mean values.

214 Multiple factor analysis (MFA) was performed on the Flash Profile ranking. Structural breakdown
215 model parameters were included (as supplementary variables) to analyse the relation between the
216 behaviour of sample in mouth and the elicited textural sensations. All analyses were performed with
217 XLSTAT statistical software (version 2019, Microsoft Excel, Adinsoft, Paris, France).

218

219 3. Results and discussion

220 3.1. Rheological behaviour of puree samples.

221 The flow behaviour of the preliminary set of carrot purees containing starch and different
222 concentrations of an extra thickener (carrageenan, CMC, xanthan gum, or starch) was measured
223 and compared to find samples with similar values of apparent viscosity at 10 s^{-1} . All puree samples
224 showed a shear-thinning flow behaviour that fitted well to the Ostwald-de Waele model ($0.96 \leq R^2$
225 ≤ 0.99). As expected, and according to previous studies, varying the type and concentration of
226 hydrocolloid resulted in purees with a wide range of consistency and flow indexes values (data not
227 showed). On inspection of flow curves, purees with different thickener and having similar flow
228 behaviour between them were selected. Table 1 shows the flow behaviour parameter values for
229 these four ET-purees and for the base puree. All showed a strong pseudoplastic (or shear-thinning)
230 character with flow index (n) values close to 0.3. This infers a structure that varies with shearing
231 because of the reorganisation or deformation of macromolecules (starch and other hydrocolloids),
232 that offer less resistance to flow at high shear rates. The addition of extra thickener affected the
233 values of consistency index (twice the value of the base puree) but did not affect the value of flow

234 index. For comparison, values of apparent viscosity at 10 s^{-1} (η_{10}) were calculated. The η_{10} values did
235 not vary, significantly, among the four ET-purees; in all cases they were significantly higher than the
236 base puree sample (Table 1). This confirms that similar apparent viscosity purees with a different
237 structure depended on the thickener.

238 [TABLE 1 HERE]

239

240 3.2. Changes in viscosity of purees under *in vitro* oral conditions

241 Figure 2 shows the changes in apparent viscosity values for the five puree samples in simulated
242 oral conditions (saliva and shearing at 10 s^{-1}) during 60 s. The values of the apparent viscosity
243 decreased progressively for a period and after remained almost constant. Viscosity values and how
244 they changed in oral conditions differed among the puree samples. As expected, the viscosity values
245 are lower for the base puree than for the other four purees with a second thickener, that shows
246 similar values of viscosity between them. However, these four purees exhibited different viscosity
247 decay patterns. We believe this is because of the nature of the structure created by each second
248 thickener, that shows different breakdown patterns under oral conditions.

249 [FIGURE 2 HERE]

250 Here, the viscosity decay is caused by three effects: shearing, dilution by saliva, and enzymatic
251 hydrolysis by saliva's amylase. Complementary essays were conducted to register the changes in
252 viscosity of purees in the same conditions but using water instead of saliva (Figure 3).

253 [FIGURE 3 HERE]

254 Comparing Figures 2 and 3, the effects of dilution and hydrolysis can be distinguished. In water,
255 the decrease in viscosity values occurred in the first three seconds with viscosity profiles similar to
256 the four ET-purees. In saliva, the decrease in viscosity was greater than in water because all samples
257 contained, as primary thickener, starch, which is affected by the action of the enzyme, α -amylase.
258 This enzyme hydrolyses (1-4) bonds of both amylose and amylopectin to form small sugar molecules
259 with the consequent structure breakdown (Chen, 2009). The viscosity decay in starch base products
260 have been previously described in custards; with less than 10 s of mixing with the saliva, the viscosity
261 of custard decreased ten-fold (Prinz et al., 2007). In the present study, the extent, and the rate of
262 decrease were different depending on the thickener. The biggest drop in viscosity was found for
263 Starch-ET-puree that showed, after the oral digestion, minimal viscosity (like the base puree)
264 because of the complete breakdown in the structure in these systems by starch hydrolysis. ET-
265 purees containing xanthan gum and carrageenan showed a small and slow decrease of viscosity
266 values. A partial breakdown of the structure caused by starch hydrolysis was observed, however,

the structure created by these two extra thickeners remained. For CMC, the viscosity drop was rapid and greater than carrageenan and xanthan gum. With CMC, starch hydrolysis removed the thickening effect of starch but also part of the CMC effect, indicating an interaction between the two thickeners. Li et al. (2008) observed cross-links between waxy rice starch and CMC, which was because of ester bonds formed between hydroxyl groups in amylopectin branches of starch and carboxyl acid groups of the CMC. This starch and CMC interaction, and its joint contribution to the structure would explain the different patterns of breakdown for our purees with CMC.

To quantify the differences among samples, the viscosity decay curves were fitted to a structural kinetic model ($0.82 \leq R^2 \leq 0.99$) and the values of the corresponding parameters were compared. Figure 4 shows the breakdown model parameters: η_0 , k , and η_e to the second-order equation. ANOVA showed that η_0 and η_e significantly varied among puree samples ($F(\eta_0) = 33.99$, $p < 0.001$; $F(\eta_e) = 24.095$, $p < 0.001$), but no K ($F(K) = 1.794$, $p = 0.207$). Here, the ET-purees have similar initial viscosity values (2.45 - 2.52 Pa.s) significantly higher than the base puree. The values of K were higher for CMC and Starch-ET-Purees, showing a more rapid breakdown. The viscosity at equilibrium (η_e), that measures the strength of the remaining structure, was lower for those purees with only starch (no other thickener), that had a lower viscosity. Purees with added xanthan, CMC, and λ -carrageenan could partially keep their structure, and the η_e was significantly higher, especially for xanthan gum and λ -carrageenan. Using the model allowed us to quantify differences in oral structure breakdown.

[FIGURE 4 HERE]

It should be notice that in this experiment a fixed amount of saliva has been used. In previous studies working on in-vitro oral simulation of semisolid food, very different amounts of added saliva were used with product: saliva ratios of 1:1 (Laguna, Farrell, Bryant, Morina, & Sarkar, 2017), 4:1 (Stribițcaia, Krop, Lewin, Holmes, & Sarkar, 2020) or 30:1 (Sanz & Luyten, 2006). The product: saliva ratio 12.5: 1 was chosen in this case as representative of an intermediate value. It would be expected that varying saliva amount would modify the curves of viscosity decay. Further studies that provide more information on the structure breakdown of hydrocolloids systems when considering different saliva flow would be very useful for finding those more appropriate for xerostomia sufferers.

3.3. Mouthfeel sensations perceived during purees consumption.

In the vocabulary generation session, each participant provided between three and five terms to describe differences in texture among purees; 47 terms were obtained. Panellists used terms

relating to bulk properties like “compact, viscous, thick, watery, and light” however, others related to surface properties like “rough, lumpy, smooth, and creamy”.

MFA was applied to the ranking data tables obtained in the evaluation session. An MFA plot considering the two first factors, that explained 76.1% of total variability is shown in Figure 5. Samples are distributed according to the differences and similarities in texture sensations elicited by each participant. We observed that attributes are aligned on two main axes; the first axis (blue) accounted for roughness versus smoothness variations. They separated the base and starch-ET-purees (on the right), perceived as “lumpy / rough / sandy” from the ET-purees with carrageenan or xanthan gum (on the left), perceived as “smooth and creamy”. The second axis (red) accounted for sensations relating to thickness and differentiated the base puree, considered more liquid and waterier from the ET-purees, that were considered as more viscous and thicker.

[FIGURE 5 HERE]

Oral structure breakdown parameters were projected on the MFA plot to study the relation to texture sensations. The initial viscosity parameter (η_0) related to the thickness sensation axis. This is in agreement previous studies, that have proposed apparent viscosity at 10 s^{-1} as an instrumental index of the thickness perceived in semisolid foods (Arcia, Costell, & Tárrega, 2010; Ross et al., 2019; Sharma, Kristo, Corredig, & Duizer, 2017). The variation in the values of viscosity at equilibrium (η_e) was related with the smoothness / roughness sensation. Samples exhibiting low η_e (containing only starch) were considered “rough, lumpy and fibrous”, while purees thickened with carrageenan and xanthan, exhibited the highest η_e and were described as “smooth and creamy”. Smoothness and roughness perception in purees is explained by the characteristics of remaining structure after saliva digestion. In purees containing only starch, the continuous matrix (starch) was destroyed by α -amylase, inner puree inhomogeneity's like carrot pieces or fibres, were then perceived, thus described as “lumpy, rough, grainy or sandy”. For ET-purees containing carrageenan and xanthan, the α -amylase resistance resulted in a remaining structure (higher viscosity after digestion), creating a layer that entraps the puree inhomogeneities and hides them. This confers product characteristics like smoothness and creaminess allowing the puree contents to be imbibed. Previous authors report xanthan and CMC confer oily mouth coating in carrot purees (Sharma et al., 2017), xanthan reduces granularity perception in potato purees (Fernández, Canet, & Álvarez, 2009), and carrageenan increases creaminess of starch-based desserts (Tarrega & Costell, 2006) In this study, the relation of these sensations with the characteristics of the structure breakdown in mouth measured *in vitro* have been demonstrated in purees.

331 The variation in parameter K, that indicates the rapidness of the breakdown in mouth, did not
332 show a relation with any specific texture sensation, as the differences are slight they are not
333 perceived, or they are not relevant for this category of product.

334 Further studies with an experimental design allowing bigger differences in the rate of the
335 breakdown in other products, like sauces, dairy creams, etc. would be necessary to discern if this
336 parameter is related to other mouthfeel sensations like melting or coating, among others.
337 Furthermore, including microstructure data will allow a deeper understanding of the mechanisms
338 behind these relationships.

339

340 4. Conclusion

341 This study proposed an approach to measure *in vitro* and to model the oral breakdown of the
342 structure of semisolid products containing starch. The differences in the breakdown patterns can
343 be quantified using three parameters that indicate the initial viscosity of the product with saliva, the
344 rate of breakdown, and the viscosity of the remaining structure after the oral digestion.

345 Purees with vastly different structural patterns can be achieved by combining starch and
346 different thickeners (carrageenan, xanthan gum, and CMC). Starch and CMC showed a rapid and
347 important breakdown of structure, while for xanthan gum and carrageenan the decay was slow and
348 smaller. A smoothness / roughness dimension was related to equilibrium viscosity parameter, thus
349 explained the characteristics of the remaining structure after the oral digestion.

350

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357

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Table 1. Mean values and standard deviation (in parentheses) of flow behaviour parameters: consistency index (K) and flow index (n) and viscosity (η_{10}) at 10 s⁻¹ of the purees with the different thickeners.

Puree Sample	K (Pa.s ⁿ)	n	η_{10} (Pa.s)*
None (Base puree)	12.67 (0.35)	0.361 (0.003)	2.91 ^a (0.10)
Starch-ET	28.15 (3.51)	0.337 (0.001)	6.13 ^b (0.91)
Carrageenan-ET	26.67 (2.74)	0.367 (0.003)	6.20 ^b (0.59)
CMC-ET	29.77 (0.21)	0.333 (0.003)	6.42 ^b (0.06)
Xanthan-ET	26.85 (0.57)	0.289 (0.004)	5.23 ^b (0.07)

*Letters indicate significant differences (Tukey test, $\alpha = 0.05$). Values not sharing letters are different

484 Table 2. Mean values and standard deviation of the initial viscosity (η_0), rate of viscosity drops (k)
 485 and apparent viscosity at equilibrium (η_e)

Puree Sample	η_0 (Pa.s)	K (s ⁻¹)	η_e (Pa.s)
Base	1.67 ^c (0.01)	0.09 ^a (0.02)	0.79 ^{bc} (0.06)
Starch-ET	2.10 ^{bc} (0.35)	0.07 ^a (0.02)	0.43 ^c (0.15)
Carrageenan-ET	2.34 ^{ab} (0.14)	0.04 ^a (0.016)	1.45 ^a (0.39)
CMC-ET	2.55 ^{ab} (0.033)	0.14 ^a (0.085)	1.03 ^{ab} (0.17)
Xanthan-ET	2.79 ^a (0.22)	0.08 ^a (0.02)	1.47 ^a (0.22)

486 For each parameter, letters indicate significant differences (Tukey test, $\alpha = 0.05$). Values not sharing letters are different.

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Figure 1. Flow chart of puree sample preparation

Figure 2.

Viscosity decay at constant shear rate of 10 s^{-1} in presence of saliva for carrot purees with starch (O) and an extra thickener: starch-ET (O), carrageenan-ET (Δ), CMC-ET ($\square$), and xanthan-ET ($\diamond$). Solid lines indicate the data fitting to a second order equation.

Figure 3. Viscosity decay at constant shear rate of 10 s^{-1} in presence of water for carrot purees with starch (O) and an extra thickener: starch-ET (O), carrageenan-ET (Δ), CMC-ET ($\square$), and xanthan-ET ($\diamond$).

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570 Figure 4. Mean values and standard deviation of the initial viscosity (η_0), viscosity at equilibrium (η_e)
571 and rate of viscosity drops (k) of the purees. Base puree (■) and purees with different extra thickener:
572 starch (■), carrageenan (■), CMC (■) and xanthan (■)For each parameter, letters indicate significant
573 differences (Tukey test, $\alpha = 0.05$). Values not sharing letters are different.
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598 Figure 5. MFA plot of sensory evaluation of puree samples by Flash Profile in relation to oral viscosity
 599 decay parameters.

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