APPLICABILITY OF THE FOODTEXTURE PUFF DEVICE FOR RHEOLOGICAL CHARACTERIZATION OF VISCOUS FOOD PRODUCTS

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Accepted Manuscript.

The published version can be found at
http://onlinelibrary.wiley.com/doi/10.1111/jtxs.12118/abstract

Please refer as: Sofie Morren, Tim Van Dyck, Frank Mathijs, Stijn Luca, Ruth Cardinaels, Paula Moldenaers, Bart De Ketelaere, Johan Claes, Applicability of the foodtexture puff device for rheological characterization of viscous food products, J. Text. Studies, DOI: 10.1111/jtxs.12118

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Abstract

The Foodtexture Puff Device (FPD) is a non-contact rheological measurement device, which applies an air pulse on the sample and measures the subsequent deformation of the sample surface with a laser distance sensor. The deformation behavior is considered as a measure for the rheological properties of the sample. The applicability of this device was studied for use on viscous food products with a broad range of rheological characteristics. In this study, sugar and fat based systems with a viscosity range of respectively 0.001 Pa.s to 6.1 Pa.s and 0.01 Pa.s to 5.9 Pa.s were tested. Comparison of the FPD with classical rheological analyses showed that the maximum deformation created by the FPD is strongly correlated to the viscosity. Hence, the FPD is well suited for measurements on sugar based and fat based systems. It is capable of providing accurate, non-contact, fast, easy and non-destructive rheological measurements on food products.

Keywords

Foodtexture Puff Device (FPD), rheology, sugar solution, fruit puree, oil, molten chocolate

Practical Applications

The Foodtexture Puff Device (FPD) is a new, non-contact rheological measurement device that can be used for a wide range of food products, including sugar solutions, fruit purees and concentrates, oils and fats, molten chocolate, batter, soft pastry, amongst others. Also more solid food products like dough can be measured accurately. The device outputs a displacement signal over time from which information can be extracted. For simple behaviors this can be performed based on one or a few characteristic values derived from the signal. For more complex foodstuff the signal as a whole can be used, and techniques such as Partial Least Squares (PLS) can be used to create a calibration curve that translates the full displacement signal over time into the desired rheological values. Seen the fact that measurement time is short, the FPD is suitable for in line as well as for R&D applications and can replace classical devices that are often time consuming and require sample preparation.

Introduction

Rheological measurements can be divided into two main groups, i.e. objective tests (using instrumentation) and sensory tests (based on human perception). Objective tests are performed by means of instruments, sensory tests by persons. Objective tests can be subdivided into fundamental and empirical tests. An overview of the major rheological measurement techniques is given in Figure 1. In fundamental tests, a well-defined sample geometry is subjected to controlled stress or strain conditions. The test can be carried out with a rheometer or in some cases a texture analyzer or viscometer. A texture analyzer can only perform fundamental measurements when the exact dimensions of the sample are known. Thereby, the strain rate needs to be adapted in function of the deformation of the sample.

Experiments with a viscometer is fundamental when using the small sample cup, whereby the cup and spindle have well-defined dimensions. These measurements are generally slow to perform and require expensive equipment. Empirical tests are derived from practical experience. These tests are usually easy to perform, rapid and less expensive. The main disadvantage of this type of measurement for use in the food industry is that mostly there are no ISO standards available. Examples of equipment used for this type of tests are a Bostwick consistometer, a viscometer and a texture analyzer (Bourne, 2002). The Foodtexture Puff Device is another example of an empirical apparatus.

Existing devices for rheological charaterization have several disadvantages. First of all, the samples often need to be manipulated, which can destroy or alter their microstructure. Secondly, the measurements are usually slow to perform. For the viscometer, which can only provide relative viscosity values, the dimensions of the measuring recipient and spindle need to be identical for comparisons of different measurements. Very simple methods, such as tests with a Bostwick consistometer, are not very precise. Consequently, it is impossible to distinguish between samples with small differences in rheological behavior. Moreover, the Bostwick consistometer is only useful for a small range of products, i.e. products with a low to medium viscosity (Bourne, 2002).

The Foodtexture Puff Device (FPD), a test that is used in the present investigation, does not have these disadvantages. The FPD is a fast, non-destructive and non-contact device that is easy to use. Furthermore, the sample preparation step is only very limited or even absent. Additionally, the sample can mostly be examined in the original packaging. Hence, it will not be disturbed and its microstructure will remain intact. For the food industry, those characteristics are very appealing and limit the effect of the major advantage of the FPD is the combination of a fast and easy, yet objective, measurement. In that way, the production can be monitored closely while human errors. Because the measurement signal is very rich, also applications in R&D are possible, when using the Partial Least Squares (PLS) technique that extracts the relevant information from the full signal.

The working principle of the FPD is based on the generation of a controlled air pulse towards the sample surface and measuring the resulting deformation of the sample surface with a laser distance sensor. The resulting deformation is considered as a measure for the rheology of the sample. This principle was first introduced by Prussia et al. (1994). Their patent described a design for measuring the firmness of fruit in an efficient, non-contact and non-destructive way. Furthermore, the authors spent much effort on improving the robustness of the method for products with a rough and uneven surface. In their research, the Magnus-Taylor puncture test was used as a reference measurement to determine the firmness of the fruit. Hung et al. (1999) investigated the applicability of the device for measuring the firmness of peaches and reported high correlations with the penetrometer firmness and peach mass. A similar device was developed by McGlone et al. (1999). McGlone and Jordan (2000) investigated the applicability of this device for use on kiwifruit and apricots and concluded that the device was only suitable for coarse screening of fruit. Lee et al. (2008) studied this method for use on raw poultry meat to predict the tenderness of the cooked poultry meat. As a reference, the tenderness of the cooked poultry meat was measured instrumentally with the Meullenet-

Owens and Blunt-Meullenet-Owens razor shear, and with sensory analysis. The deformation resulting from the air pulse, is a good measure for the tenderness of the cooked poultry meat.

Based on the idea of Prussia et al. (1994), Bamelis and De Baerdemaeker (2006) developed the FPD to monitor the coagulation of milk during cheese-making. The FPD differed from the idea of Prussia et al. because that device was only suitable for use on solid products like fruit and poultry meat. Thus it was never tested before on liquid products. Bamelis and De Baerdemaeker found a clear correlation between the deformation measured by the FPD and the firmness (i.e. storage modulus) of the cheese-curd at different stages of the coagulation. Moreover, the device seemed to be appropriate for fast laboratory measurements and in line applications.

In the present study, the use of the FPD for rheological measurements on sugar solutions, glucose syrups, fruit purees and concentrates, oils and fats, and chocolate, will be assessed. Rotational measurements with a classical rheometer were carried out as a reference. The fundamental rheological measurement protocols were chosen based on typical characterization methods for the different food samples, as described in literature. In the present article, the focus is on viscosity as a reference measure. For dough systems, also viscoelastic properties were related to the FPD signal. This is, however, beyond the scope of the present article.

Materials and methods

Preparation of samples

Sugar solutions: Seven sugar solutions were prepared with sucrose and water. Different amounts of sucrose were added to boiling water and afterwards the solutions were cooled down to the measurement temperature. A wide range of sucrose concentrations was prepared, ranging from 10 to 70 °Brix (steps of 10 °Brix). The sucrose concentration of the solutions was determined using a refractometer (Refractometer HI 96801, Hanna Instruments, USA) and approximated the desired value up to +/- 0.4 °Brix. Five percent of low fat milk was added to make the solutions opalescent, a desired property when using laser displacement sensors as used in the FPD (see further). The milk caused a minor change in the viscosity of the sugar solutions (maximum 5%, data not shown), but because it was added in the same amount to all samples, i.e. samples measured with the FPD and the rheometer, correlations could be made. Measurements performed with both the FPD and the rheometer were set at 7, 20 and 40 °C, resulting in a total of 21 samples.

Glucose syrups: Thirteen glucose syrups with dextrose equivalent (DE) values ranging from 27 to 97, were obtained from Cargill (The Netherlands) and Syral (Belgium). Samples were used as received and brought to the measurement temperature of 50 °C, for both measurements with the FPD and the rheometer.

Fruit purees and concentrates: Eleven ready-made fruit purees and concentrates (FrieslandCampina, The Netherlands) with diverse types of fruit (peach, pear, strawberry,

cranberry…) were also examined. Measurements performed with both the FPD and the rheometer were executed at 7, 20 and 40 °C.

Oils and fats: Twelve samples of oils and fats (sun flower oil, olive oil, refined soy oil, hydrogenated soy oil, refined palm oil, hydrogenated palm oil, refined rapeseed oil, hydrogenated rapeseed oil with three degrees of hydrogenation, i.e. 15, 23 and 36 and two types of free fatty acids) with a wide variety of fatty acids were investigated (Cargill, The Netherlands; FrieslandCampina, The Netherlands; Vandemoortele, Belgium). The oils and fats were molten in a water bath before analysis. 0.2 wt% titanium oxide was added to all the samples measured with the FPD and the rheometer, making the oils and fats opalescent and the samples surface detectable for the laser distance sensor of the FPD. This had no influence on the rheological properties of the oils and fats. The measurement temperatures of the oils and fats, for both the FPD and the rheometer measurements, were 25 °C, 40 °C, 55 °C and 70 °C. The fat samples were not measured at 25 °C, because of the higher melting point.

Chocolate samples: Finally, nine chocolates (several types of fondant, milk and white chocolate) (Belcolade, Belgium; Cargill, Belgium) with different composition, and thus viscosity values, were molten in a water bath with a controlled temperature of 50 °C. Standardization was obtained by stirring the chocolate after it was molten, followed by 20 minutes of rest in the water bath at 42 °C. Measurements performed with both the FPD and the rheometer were performed at 40 °C.

All measurement temperatures were achieved by placing the samples in a beaker which was placed in a water bath with controlled temperature, except for the measurements at 7 °C. Tests at 7 °C were carried out on samples directly taken from the refrigerator at 7 °C. Tests were started when temperature equilibrium was reached. No further temperature control was required during the experiments with the Foodtexture Puff Device (FPD) since it is a fast measurement method (maximum duration of a measurement is 5 s).

Measurements with the Foodtexture Puff Device (FPD)

The Foodtexture Puff Device (FPD) applies a controlled air puff to the surface of the sample and the resulting deformation as function of time is measured by a laser distance sensor (Figure 2).

Several input parameters of the FPD can be set, such as air pressure and distance of the measuring head to the surface of the sample. For each sample, values for these parameters were chosen with the aim of obtaining a high reproducibility. In addition, the duration of the air pulse and measurement time can be chosen. The duration of the air pulse was set at 100 ms for the sugar based systems and at 75 ms for the fat based systems. It was found that a shorter pulse duration gave more consistent results for those fat based systems (data not shown).

The deformation as function of time is determined by the rheological characteristics of the product as is illustrated in Figure 3. Products with low viscosity values displayed an under-damped oscillatory profile (Figure 3 (a)), whereas products with a higher viscosity or flow stress showed an over-damped profile (Figure 3 (b)). The observed signal is rich in

information and can be described using several characteristic values such as the maximum deformation, the overshoot and the rest value. The maximum deformation is the minimum value obtained, whilst the overshoot is the maximum value obtained. The rest value is the value reached at the end of the measurement. Based on our investigation, the maximum deformation is for most food products that display a rather simple behavior the most informative parameter. For this reason, the maximum deformation was mostly used to compare with the viscosity, obtained from the reference method.

The dimensions of the measuring recipients are given in Table 1. For all the samples, except for the molten chocolate, the same beaker was used. For products with a low viscosity, the beaker size influences the measurement profile, due to the reflection wave of the liquid against the recipient wall. However, for a diameter of 65 mm, this wave does not influence the maximum deformation or the overshoot (data not shown). Molten chocolate was examined using a beaker with a larger diameter to perform multiple measurements at different locations.

Firstly, sugar based systems (sugar solutions, glucose syrups, fruit puree and concentrates) were measured with the FPD. To make sure all the sugar is in solution, all samples were stirred before starting the measurement, as well as before each repetition. Sugar solutions have very low viscosity values (less than 0.1 Pa.s), requiring low air pressure values. A beaker with the sugar solution was placed under the measuring head of the FPD. All the sugar solutions were measured at a distance of 35 mm and using an air pressure of 200 mbar. As an additional experiment, the air pressure of the sugar solutions with 10 and 50 °Brix was also varied from 50 to 500 mbar to investigate the linearity of the deformation with respect to the air pressure. Ten repetitions for each concentration were performed. Glucose syrups have higher viscosities and thus require a higher air pressure. Glucose syrups were measured in a range of 500 to 1500 mbar at 35 mm distance. Five repetitions were performed. Fruit purees and concentrates were measured at a distance of 35 mm, with an air pressure of respectively 250, 750 and 2000 mbar, depending on the viscosity of the sample. Certain fruit purees and concentrates were measured in an air pressure range. Three repetitions were carried out, each on a new sample (Table 2).

Secondly, fat based systems (oils and fats, and molten chocolate) were measured using the FPD. Oils and fats were measured at 50 and 200 mbar at a distance of 45 mm. Ten repetitions were performed on each oil sample. For molten chocolate, the specific beaker was placed under the measuring head of the FPD. Then six repetitions on equidistant places at the samples surface were carried out, using a constant air pressure. After this measurement, the molten chocolate was stirred in the beaker and put in the water bath at 42 °C for 20 minutes to rest. This resting period was important because of the thixotropic behavior of molten chocolate. After 20 minutes, again six repetitions were performed, but this time using another air pressure. With this procedure, the air pressure for molten chocolate ranged from 100 to 2500 mbar with steps of 100 mbar (distance from the head to the surface was 25 mm) (Table 2).

Fundamental rheological measurements

Fundamental rheological measurements were carried out with a rheometer with a Peltier system to control the temperature (Physica MCR 301, Anton Paar Benelux BVBA, Gentbrugge, Belgium). Rotational measurements were performed on all samples to determine the viscosity. For every product, three repetitions were performed using a new sample for each repetition.

The viscosities of sugar solutions were determined in a shear rate ramp with a concentric cylinder system with a ratio of inner to outer radius of 0.96. The shear rate was varied from 0.1 to 100 s^{-1} over 155 s (Yoğurtçu and Kamişh, 2006). The slope of the curve (shear stress in function of shear rate), was taken as the viscosity. This was possible because of the Newtonian behavior of sugar solutions. Glucose syrups were tested with a plate-plate system of 25 mm diameter and a gap of 1 mm. A constant shear rate of 10 s^{-1} for 120 s was applied and the mean viscosity value was taken. Fruit purees and concentrates were tested with a plate-plate system of 50 mm diameter and a gap of 2 mm. These products showed shear thinning behavior. However, to obtain a single viscosity value as a reference, these samples were analyzed at a constant shear rate of 10 s^{-1} during 250 s and every 5 s a measuring point was registered. The mean viscosity value was calculated.

Oils and fats were measured with a plate-plate system of 50 mm diameter and a gap of 1 mm. A shear rate ramp from 10 to 1000 s^{-1} over 29 s was applied and the slope of the curve obtained, shear stress in function of shear rate, was taken as viscosity value (Kim et al., 2010). The viscosity values of the molten chocolate samples were determined with a concentric cylinder system, following the standard procedure of the International Cocoa Organization (ICCO). Because of the thixotropic behavior of chocolate, reproducibility of the sample preparation has to be guaranteed. After resting for 20 minutes in the water bath, the sample was filled in the cup of the concentric cylinder and subsequently a pre-shear of 5 s^{-1} for 15 minutes was performed. For the actual test, a shear rate ramp from 5 to 50 s^{-1} (ramp up) over 120 s was applied and thereafter the shear rate was decreased from 50 to 5 s^{-1} (ramp down) in 120 s. The shear stress at a shear rate of 30 s^{-1} (ramp up) represented the viscosity (Afoakwa et al., 2009).

Statistical analyses

Statistical analyses were performed with IBM SPSS Statistics 19.0 (New York, United States). To demonstrate potential significant differences, ANOVA was carried out. After a positive omnibus F-test, Post-Hoc multiple comparisons (Duncan) were carried out. To examine whether regression lines were significantly dissimilar, an analysis of covariance (ANCOVA) model was fitted. A significance level of 5% was applied throughout all analyses.

Results and discussion

Fluid-like sugar based and fat based systems with a wide variety of viscosities were tested in this study. This variety is illustrated with the viscosity range of the different products, as obtained with the fundamental rheological measurements (Table 3).

Sugar based systems

The results of the fundamental measurements of the sugar solutions indicate the Newtonian behavior. Glucose syrups, fruit purees and concentrates have a shear-thinning behavior and fruit purees and concentrates show sometimes a thixotropic behavior as well (data not shown).

When measuring with the FPD, the sugar solutions show an under-damped oscillatory profile (similar to Figure 3 (a)), because of the very low viscosity values. On the other hand, fruit purees and concentrates show an over-damped profile (similar to Figure 3 (b)). Sometimes a rest value was detectable, probably due to the higher viscosity. A reasonable explanation for this observation is the small time frame measured, i.e. only two seconds, which is too short for a full recovery of the product surface to its starting position.

Also surface tension will have an influence on the results obtained with the FPD. However, for the systems under study (sugar solutions, glucose syrups or fruit purees and concentrates), the difference in surface tension were small as compared to the forces and deformations applied by the air pulse (data not shown).

The results of the experiments with the FPD on two sugar solutions and a fruit puree are demonstrated in Figure 4. The maximum deformation is shown as function of the air pressure. A strong linear correlation between the maximum deformation and the air pressure was found, which indicates that the FPD delivered consistent results. The correlation coefficient of the fruit puree is lower as compared to that of the sugar solutions, which is probably due to the heterogeneity of the product. Similar results were obtained for the glucose syrups. Figure 4 illustrates that the FPD is able to establish a linear pressure-deformation relation, as an equivalent of a classical stress-deformation curve. Furthermore, measurements with the FPD gave rather small standard deviations on the maximum deformation (a Coefficient of Variation of about 5%), what makes it a reproducible method. The slope and intercept of the regression line for the maximum deformation of the sugar solution of 10 °Brix differed significantly from the one of the solution with 50 °Brix. Moreover, the values of the maximum deformation of the 10 °Brix sugar solution were higher than the values of the 50 °Brix solution for each air pressure.

Figure 5 demonstrates the effect of the sugar concentration on the viscosity and corresponding deformation in the FPD measurements for a range of sugar solutions. Figure 5 (a) gives an overview of the maximum deformation values of all sugar solutions at 200 mbar. Figure 5 (b) shows the viscosity values of all the sugar solutions tested. Whereas the viscosity increases with increasing sugar concentration, the maximum deformation decreases with increasing sugar concentration. Despite the deviating result of the sugar solution with 60 °Brix, it can be seen from Figure 5 that the FPD qualitatively captures the effect of sugar concentration on the

flow behavior of sugar solutions. The dependency of the viscosity on the sugar concentration was less pronounced at low sugar concentrations and increased with sugar concentration, clearly reflecting the non-linear dependency of viscosity, and of maximum deformation, as function of sugar concentration. The curvilinear relation between the sugar concentration and the viscosity was also found by Soesanto and Williams (1981) and Quintas et al. (2006).

The temperature dependency of the maximum deformation of several sugar solutions and fruit concentrates is demonstrated in Figure 6 (a), respectively Figure 6 (b). The measurements shown were caried out at 200 mbar for the sugar solutions and at 250 mbar for the fruit concentrates. The maximum deformation increased with increasing temperature. Although the FPD was not able to make a significant distinction for the sugar solutions at each temperature, there was an apparent trend. However, for the sample with 60 °Brix, the maximum deformation was inversely proportional to the temperature. No suitable explanation for this phenomenon could be found. For the fruit concentrates, for all three types was a significant difference in maximum deformation for the three temperatures. Similar results were obtained with the rheometer (Table 4).

The correlation between the maximum deformation (FPD) and the viscosity (rheometer) at all measurement temperatures for sugar solutions and fruit purees and concentrates is depicted in Figure 7 (a) and Figure 7 (b) respectively. The correlation between the maximum deformation and viscosity values showed a strong linear relation ($R^2 > 0.9$). Because of this linear relation found for the sugar solutions, it can be stated that the FPD was able to describe the Newtonian behavior that is typical for sugar solutions (Recondo et al., 2006 and Quintas et al., 2006). For the fruit purees and concentrates, a curvilinear relation was found. However, two groups can be distinguished. The first group, at the low viscosity values, were measurements performed on fruit concentrates, whereas the second group, at the higher viscosity values, were measurements performed on fruit purees. It seems that the FPD showed a stronger capability in distinguishing the fruit concentrates than the fruit purees. Because of the good correlations between the maximum deformation and the viscosity, the FPD may replace the classical rheometer when empirical results contain sufficient information. In addition, the results from Figure 7 can be used as calibration curves which allows to calculate the viscosity from the maximum deformation.

Fat based systems

The results of the fundamental measurements confirmed the expected Newtonian behavior of the oils and fats. Molten chocolate demonstrated a shear-thinning and thixotropic behavior, and also a yield stress was detected.

As with the sugar based systems, products with low viscosity values such as oils and fats showed an under-damped oscillatory profile, whereas products with a higher viscosity such as molten chocolate showed an over-damped profile with a rest value (Figure 3).

The maximum deformation for a white molten chocolate as function of the air pressure is shown in Figure 8. A strong linear relation ($R^2 > 0.99$) of the maximum deformation and the air pressure was observed, which demonstrates the consistent results of the FPD.

Figure 9 presents a comparison of all types of chocolate at 40 °C. Figure 9 (a) shows the results of the FPD measured at 1000 mbar. The viscosity values at 30 s^{-1} are displayed in Figure 9 (b), which illustrates the wide variety of chocolate samples that was tested. When performing the post-hoc Duncan test using a significance level of 5% for the maximum deformation, all samples were significantly different. To the contrary, the rheometer could only distinguish four groups at the same significance level. As for the sugar based systems, also the fat based systems showed a relative small standard deviation in maximum deformation or overshoot (a Coefficient of Variation of approximately 6%), and therefore measurements with the FPD could be considered as being reproducible.

Figure 10 shows the temperature dependency of a refined and hydrogenated oil sample as measured using the maximum deformation and the overshoot values from the FPD (Figure 10 (a)), as well as in terms of the viscosity (Figure 10 (b)). The maximum deformation increased marginally with temperature, whereas the increase for the overshoot was more pronounced. This indicated that the overshoot is better able to distinguish very small differences in viscosity when measuring low viscosity fluids.

The viscosity of all oil samples changed exponentially as function of temperature ($R^2 > 0.9$). This temperature dependency of the viscosity is described by the Arrhenius equation (Kim et al., 2010):

$$\eta = A \cdot \exp\left(\frac{E_a}{R \cdot T}\right) \qquad \text{Equation 1}$$

with η: viscosity (Pa.s); E_a: activation energy (J); T: temperature (K); A and R are constants.

Similarly, the temperature dependency of the overshoot was modeled using an Arrhenius equation:

$$\frac{1}{overshoot} = a \cdot \exp\left(\frac{E_{FPD}}{R.T}\right) \qquad \text{Equation 2}$$

with E_{FPD}: calculated activation energy for the FPD; T: temperature (K); a and R are constants.

The results of the rapeseed oils are depicted in Figure 11. The other oils and fats showed analogous profiles. The profiles for all types of oils and fats obtained with the FPD were similar to the profiles generated with the rheometer data. The FPD was thus capable to describe the temperature dependent behavior of oils and fats.

The activation energy of all the measurements with the FPD (E_{FPD} from Eq. 2) and the rheometer (E_a from Eq. 1) is presented in Figure 12. At the lower E_a-values, a correlation seems to exist, but this was not the case at higher activation energies. It requires further research to use the FPD measurements as a measure for activation energies.

In Figure 13, the correlation between the FPD data (respectively the overshoot and the maximum deformation) and the rheometer data (the viscosity) at all measurement temperatures for the oil and fat samples (Figure 13 (a)) as well as the molten chocolate

samples (Figure 13 (b)) is presented. Measurements on oils and fats, and molten chocolate gave good curvilinear correlations ($R^2 > 0.9$). Hence, the FPD is also capable for measuring oils and fats, as well as molten chocolate.

Conclusions

The Foodtexture Puff Device (FPD) is a new rheological measurement device, which applies a controlled air pulse to the product surface and measures the subsequent deformation of the surface. The applicability of this device was studied for use on viscous food products such as sugar and fat based systems.

The correlation coefficients between the FPD and the rheometer data were strong. Sugar solutions showed a strong linear relationship between the maximum deformation and the viscosity. For fruit purees and concentrates, oils and fats, and molten chocolate, strong curvilinear correlations were established between the maximum deformation (or overshoot) and the viscosity. Furthermore, small standard deviations were obtained and the temperature dependency could be demonstrated with the FPD. These results pointed out the applicability of the FPD for a wide range of food products, i.e. products with a wide viscosity range. Moreover, the FPD is well suited for in line applications, because it is an easy, fast, non-contact and non-destructive measurement. Besides inline applications, the FPD is also appropriate for R&D applications, because it is an accurate device with strong correlations with classical rheological methods. When more detailed information about the rheological characteristics is needed, the integrated PLS in the software of the FPD can be used. In further work also viscoelastic food products will be studied.

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TABLE 1.
DIMENSIONS OF THE MEASURING RECIPIENTS

	Sugar solutions	**Glucose syrups**	**Fruit purees / concentrates**	**Oils and fats**	**Molten chocolate**
Diameter (mm)	65	65	65	65	150
Height (mm)	75	75	75	75	70

TABLE 2.
PARAMETERS OF THE FPD MEASUREMENTS

Parameters FPD	**Sugar solutions**	**Glucose syrups**	**Fruit puree / concentrates**	**Oils and fats**	**Molten chocolate**
Air pressure (mbar)	200*	500 to 1500	250 / 750 / 2000	50 / 200	100 to 2500
Distance (mm)	35	35	35	45	25
Duration air pulse (ms)	100	100	100	75	75
Measurement time (ms)	2500	2500	2500	2500	2500
Repetitions	10	5	3	10	6

* For the sugar solutions with 10 and 50 °Brix, also an air pressure range from 50 to 500 mbar was performed.

TABLE 3.
OVERVIEW OF THE RHEOLOGICAL RESULTS (THE GIVEN VISCOSITIES ARE THE MINIMUM AND MAXIMUM VALUES MEASURED FOR THE DIFFERENT SAMPLES)

	Viscosity (Pa.s)
Sugar solutions	0.001 – 0.1
Glucose syrups	0.75 – 14.4
Fruit purees and concentrates	0.02 – 6.1
Oils and fats	0.01 – 0.1
Molten chocolate	0.37 – 5.9

TABLE 4.
VISCOSITY VALUES (PA.S) OF THREE FRUIT CONCENTRATES AT DIFFERENT TEMPERATURES

		7 °C	20 °C	40 °C
Sugar solutions	20 °Brix	3.020	2.051	1.303
	40 °Brix	10.378	6.251	3.398
	60 °Brix	94.106	42.889	16.844
Fruit concentrates	Pear	1.070	0.351	0.052
	Peach	0.405	0.143	0.031
	Blackberry	0.174	0.077	0.021

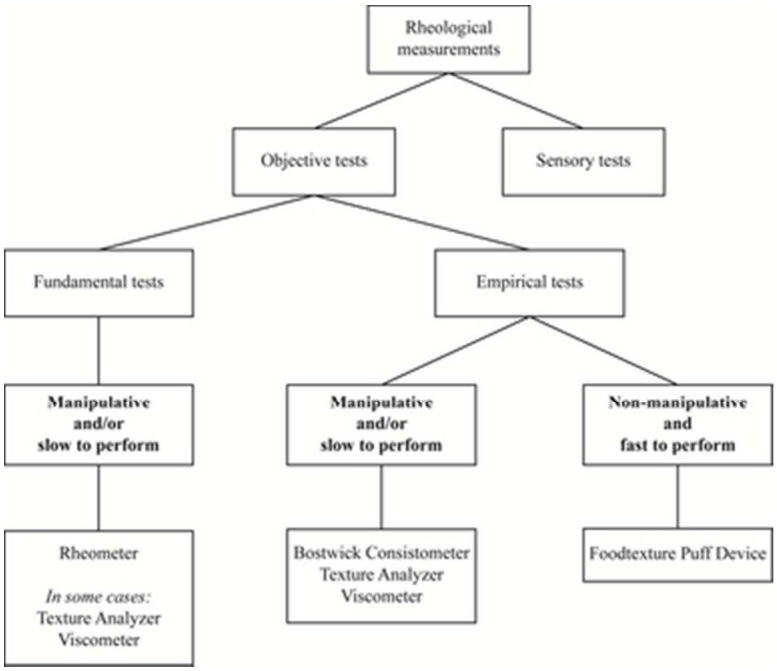

Figure 1: Schematic representation of rheological measurements (from Bourne, 2002)
32x27mm (300 x 300 DPI)

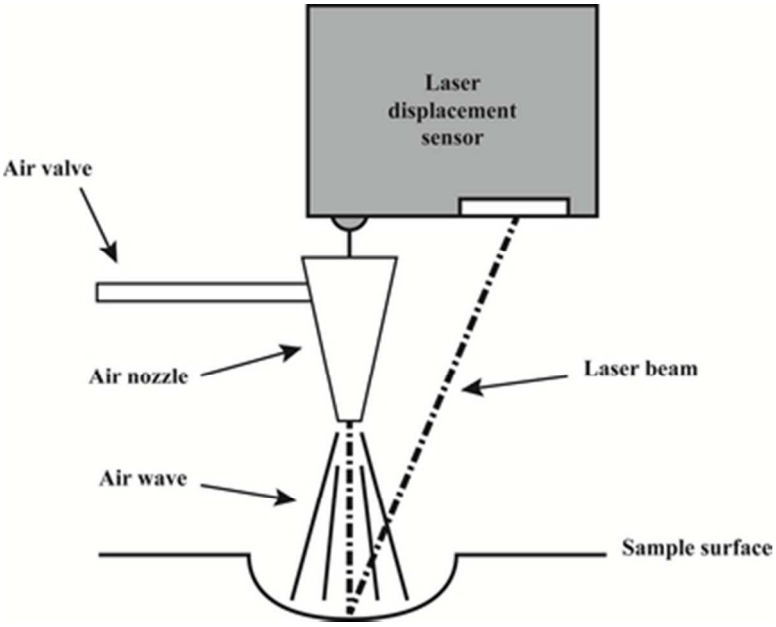

Figure 2: Working principle of the FPD (Bamelis and De Baerdemaeker, 2006)
32x26mm (300 x 300 DPI)

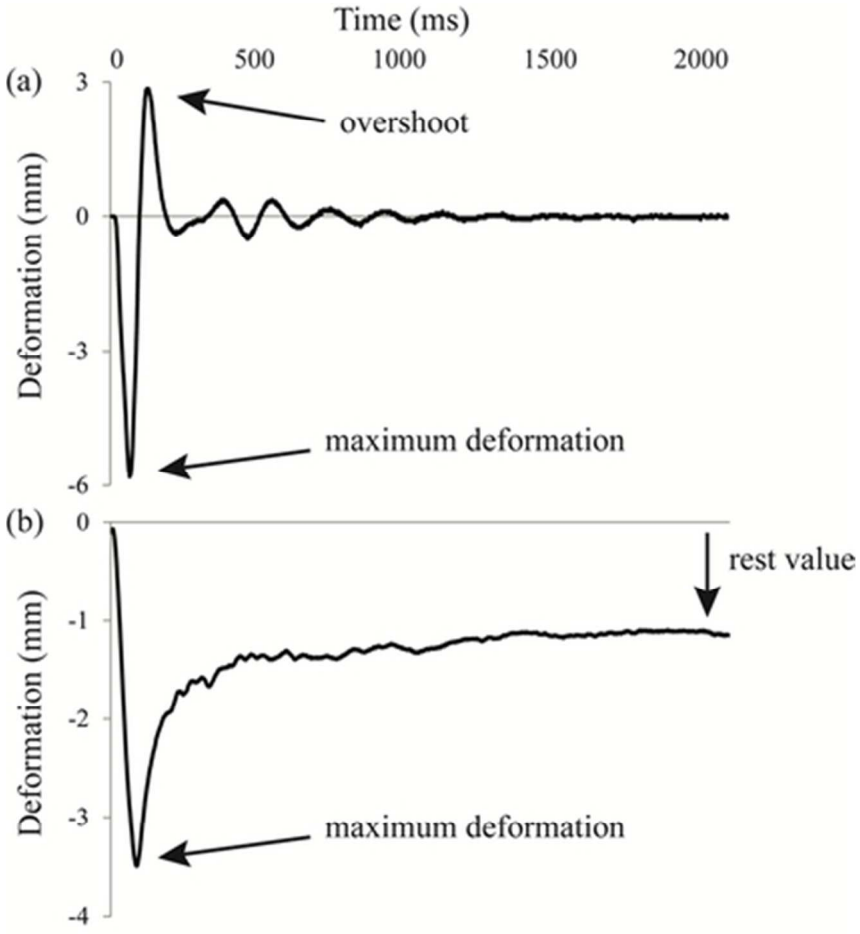

Figure 3: Two typical FPD profiles of low viscosity fluids (rapeseed oil at 25 °C) (a) and high viscosity fluids (molten chocolate at 40 °C) (b)
35x39mm (300 x 300 DPI)

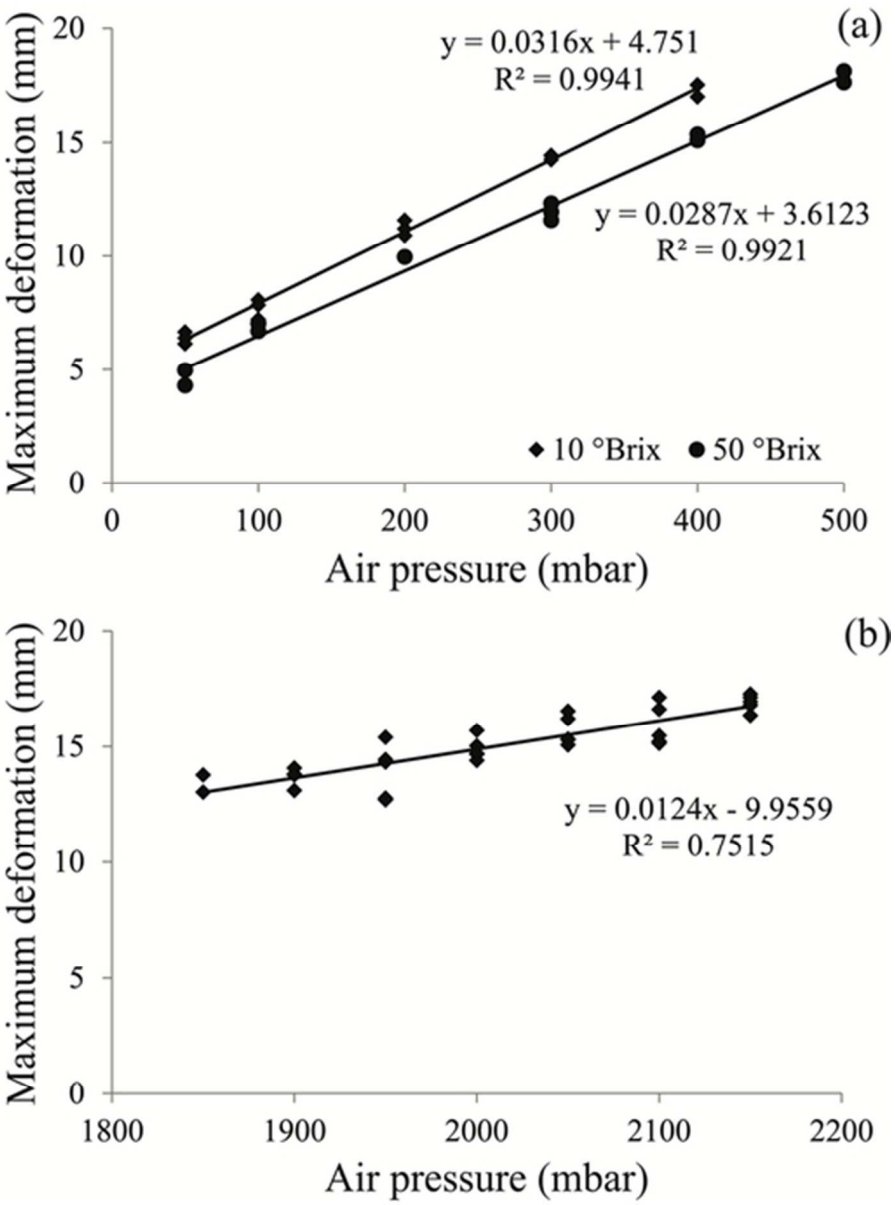

Figure 4: Maximum deformation of two sugar solutions (10 and 50 °Brix) at 20 °C (a) and a fruit puree (peach/pear) at 7 °C (b) as function of air pressure
43x58mm (300 x 300 DPI)

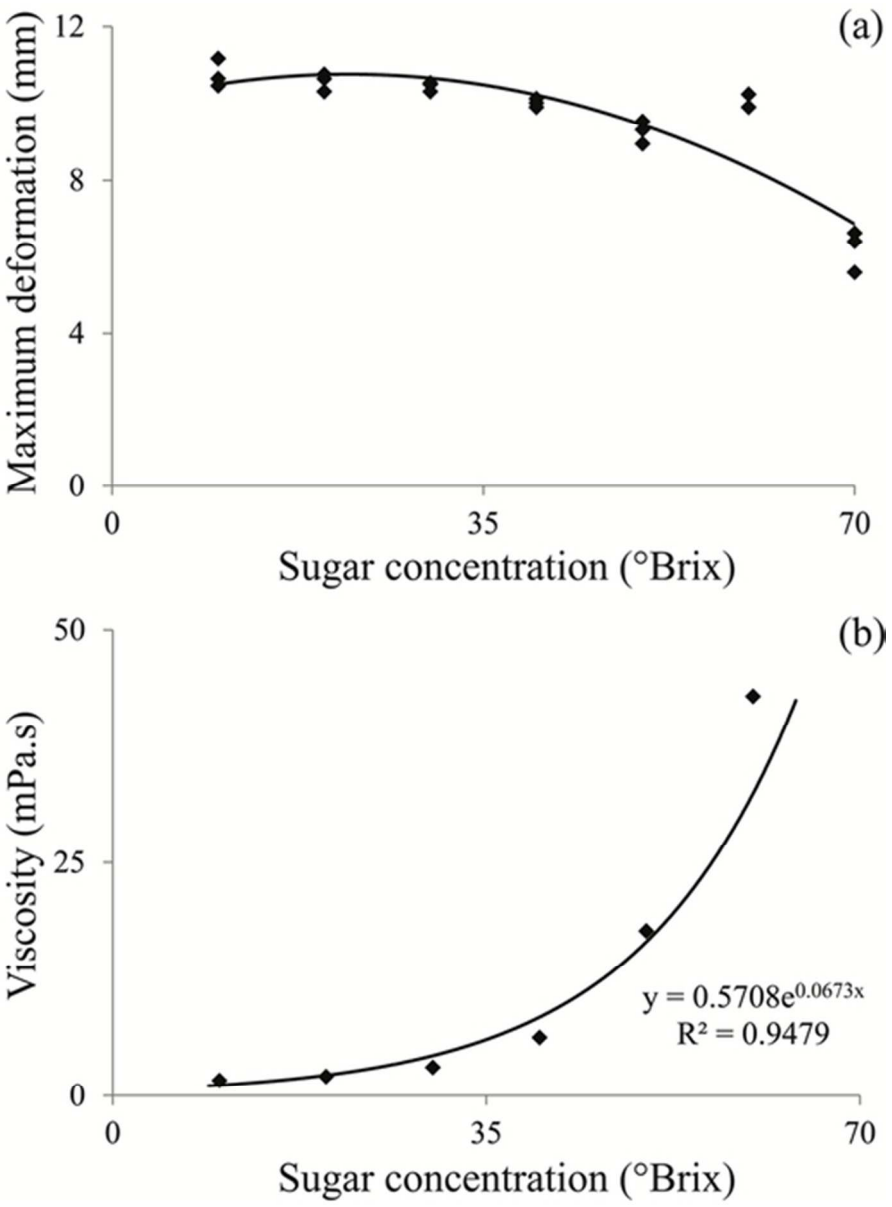

Figure 5: Maximum deformation (a) and viscosity (b) at 20 °C as function of sugar concentration
43x58mm (300 x 300 DPI)

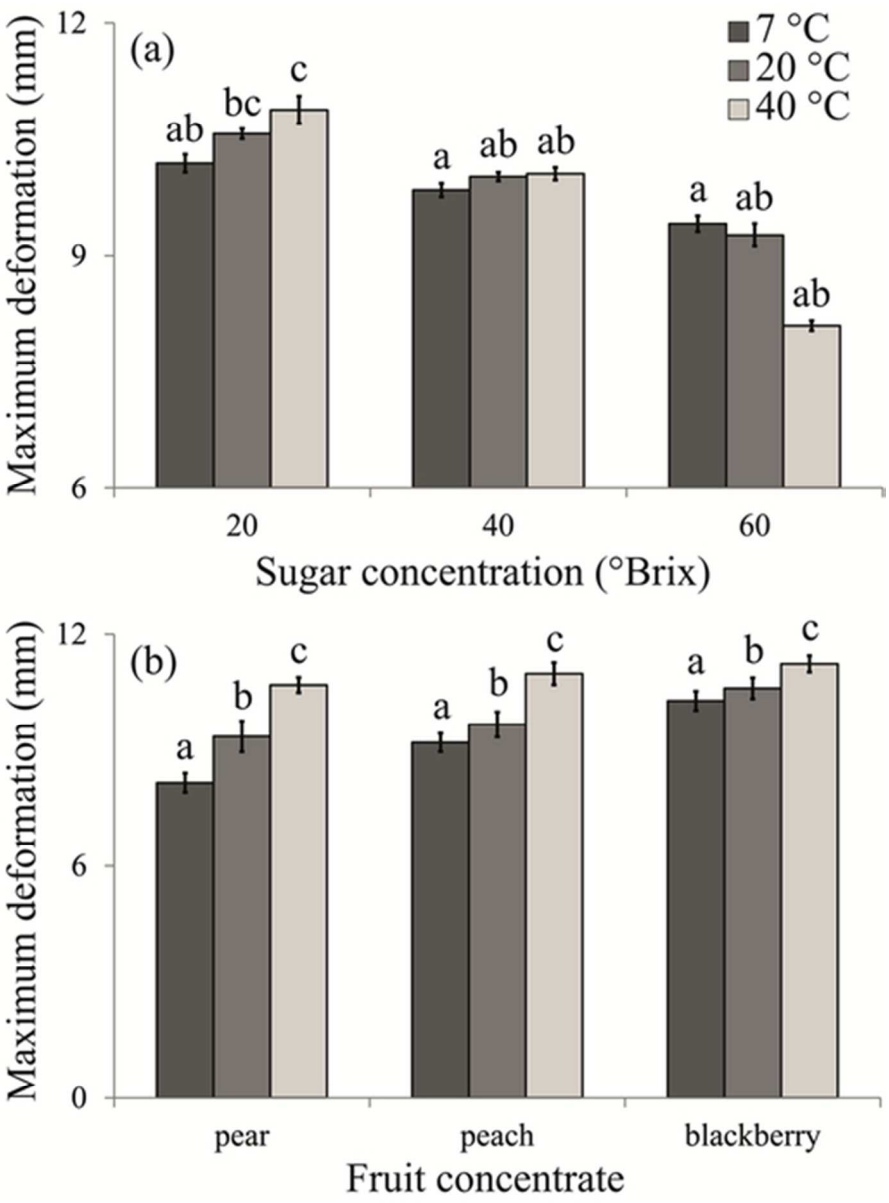

Figure 6: Temperature dependency of sugar solutions (a) and fruit concentrates (b). Different letters above the bars indicate significant differences with a significance level of 5%.
43x58mm (300 x 300 DPI)

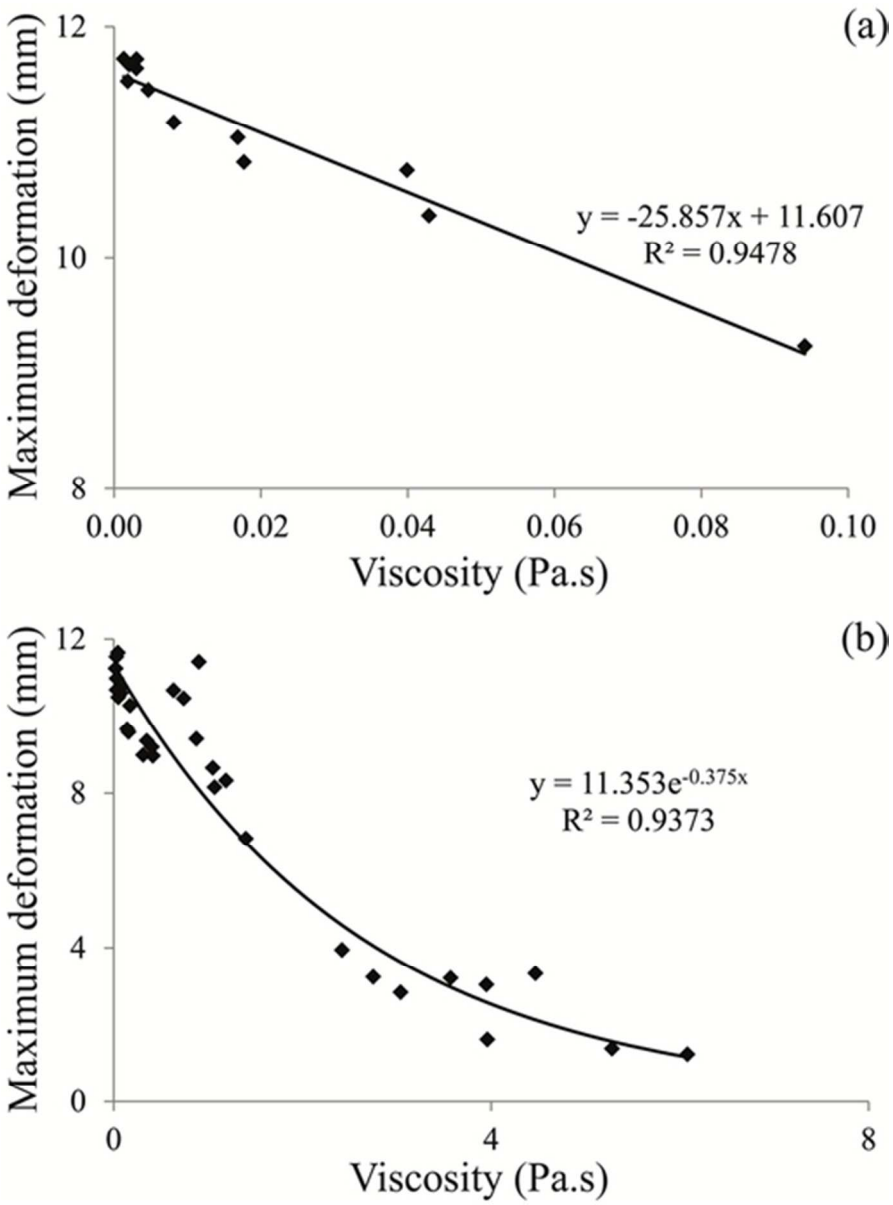

Figure 7: Correlation between FPD and rheometer of sugar solutions (a) and fruit purees and concentrates (b)
43x58mm (300 x 300 DPI)

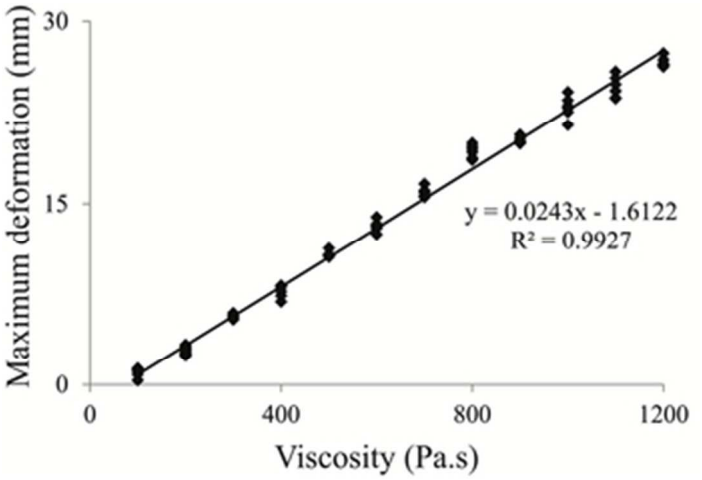

Figure 8: Example of a white molten chocolate (40 °C), analyzed with several air pressures
29x20mm (300 x 300 DPI)

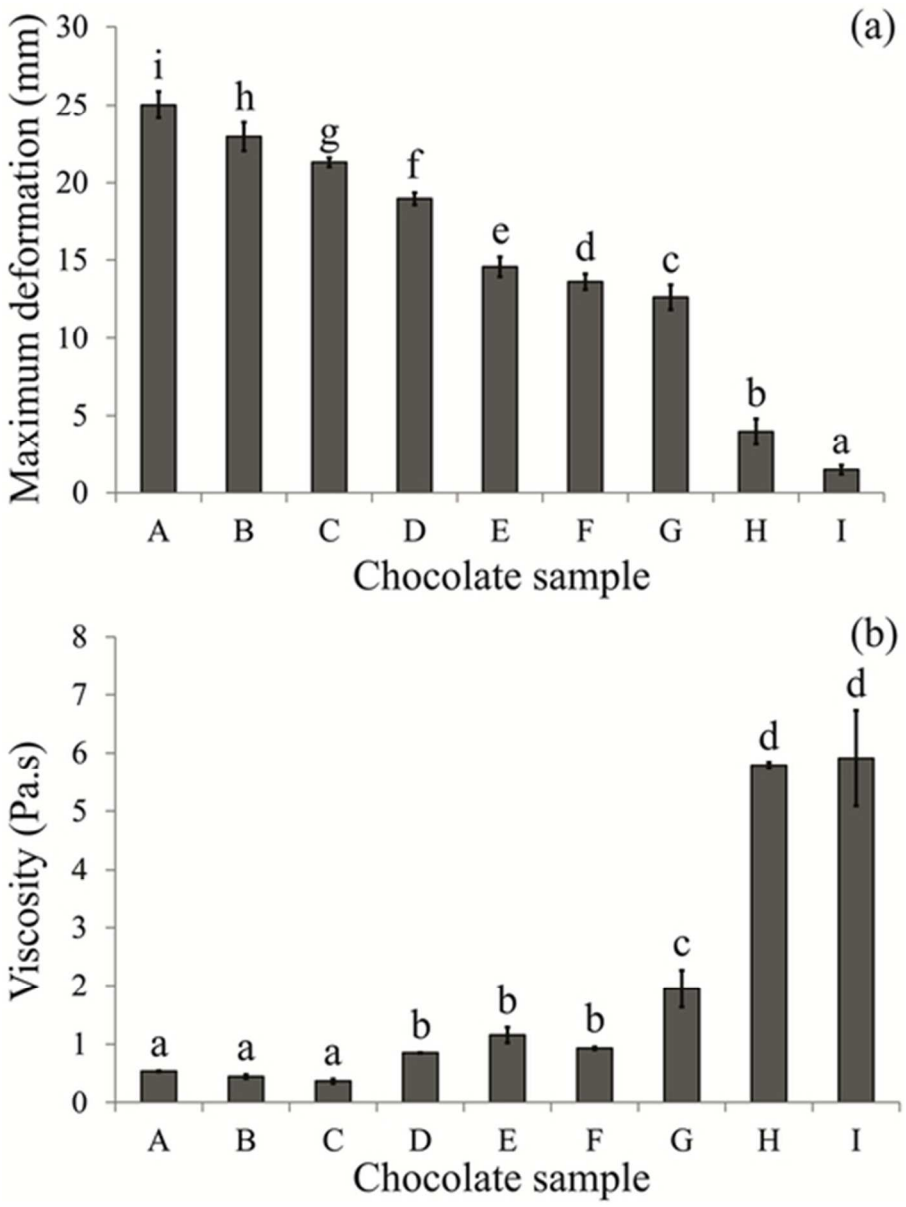

Figure 9: Maximum deformation values (a) and viscosity values (b) of all chocolate samples at 40 °C. Different letters above the bars indicate significant differences with a significance level of 5%.
42x56mm (300 x 300 DPI)

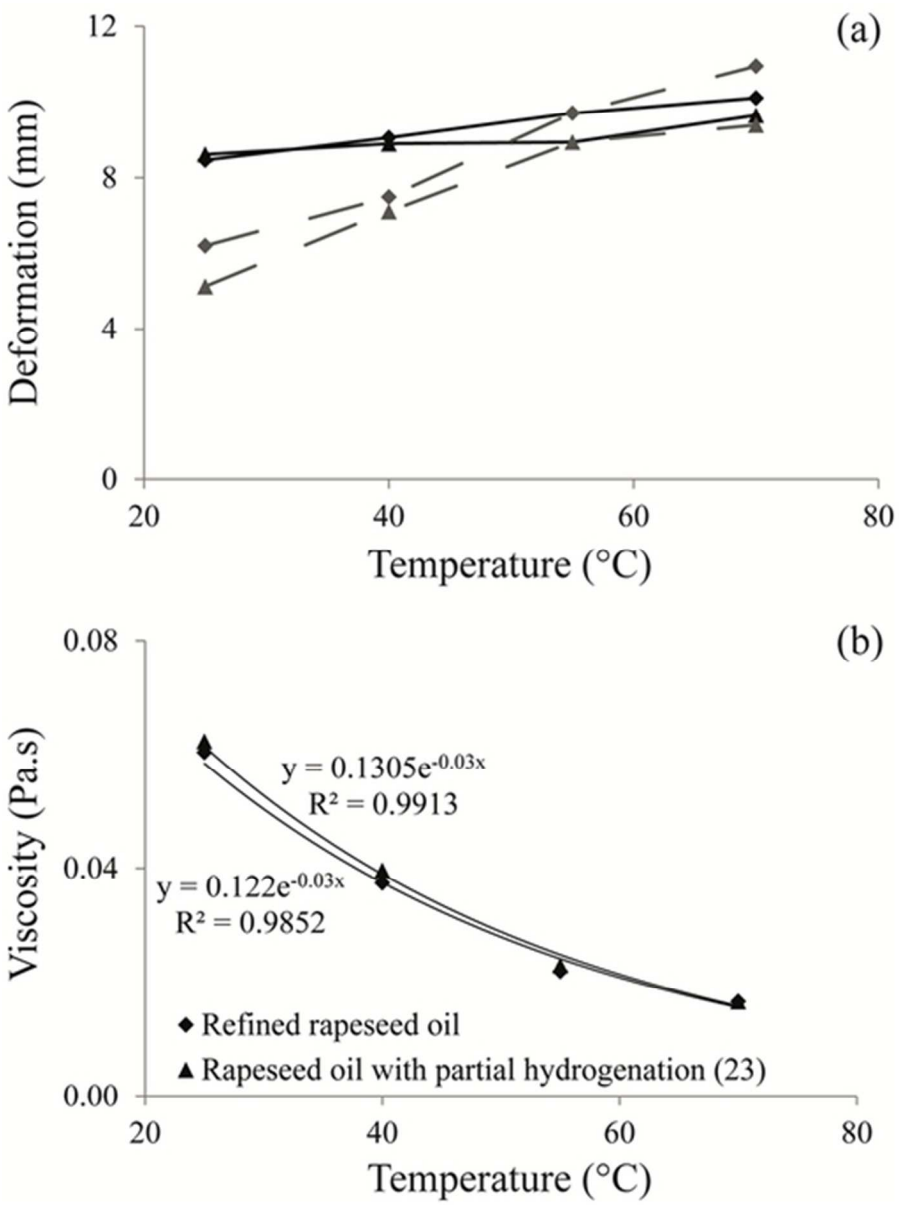

Figure 10: Maximum deformation (black) and overshoot (grey) (a) and viscosity (b) as function of temperature
43x57mm (300 x 300 DPI)

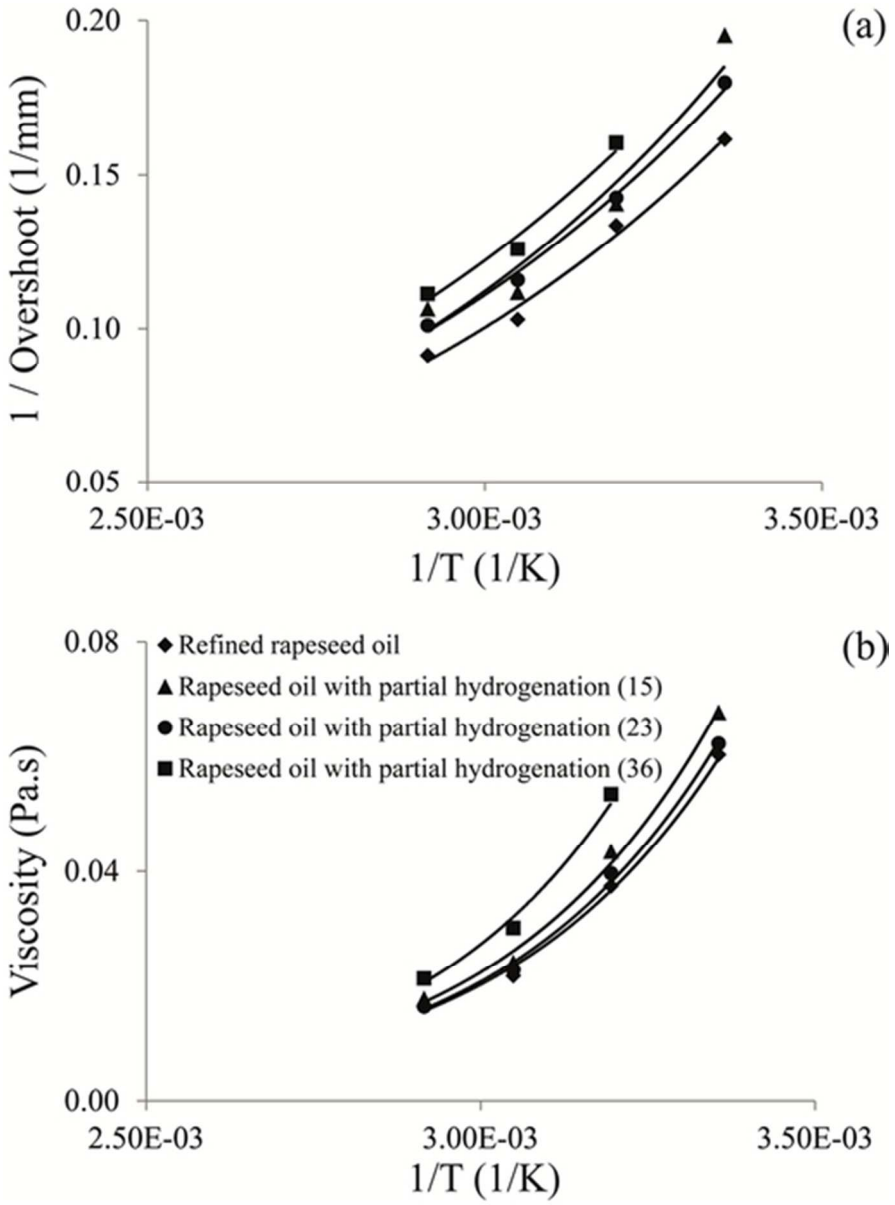

Figure 11: 1 / Overshoot (a) and viscosity (b) as function of 1/T for rapeseed oil at several degrees of hydrogenation
43x58mm (300 x 300 DPI)

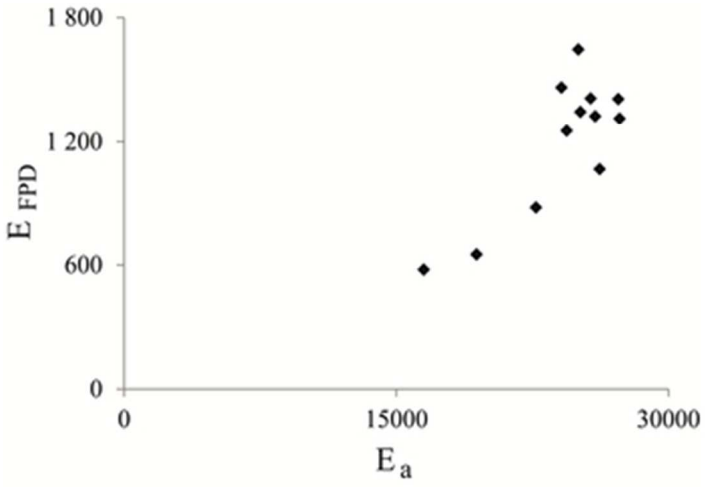

Figure 12: Correlation of the calculated activation energy from the rheometer data (Ea) and the FPD data (EFPD)
29x20mm (300 x 300 DPI)

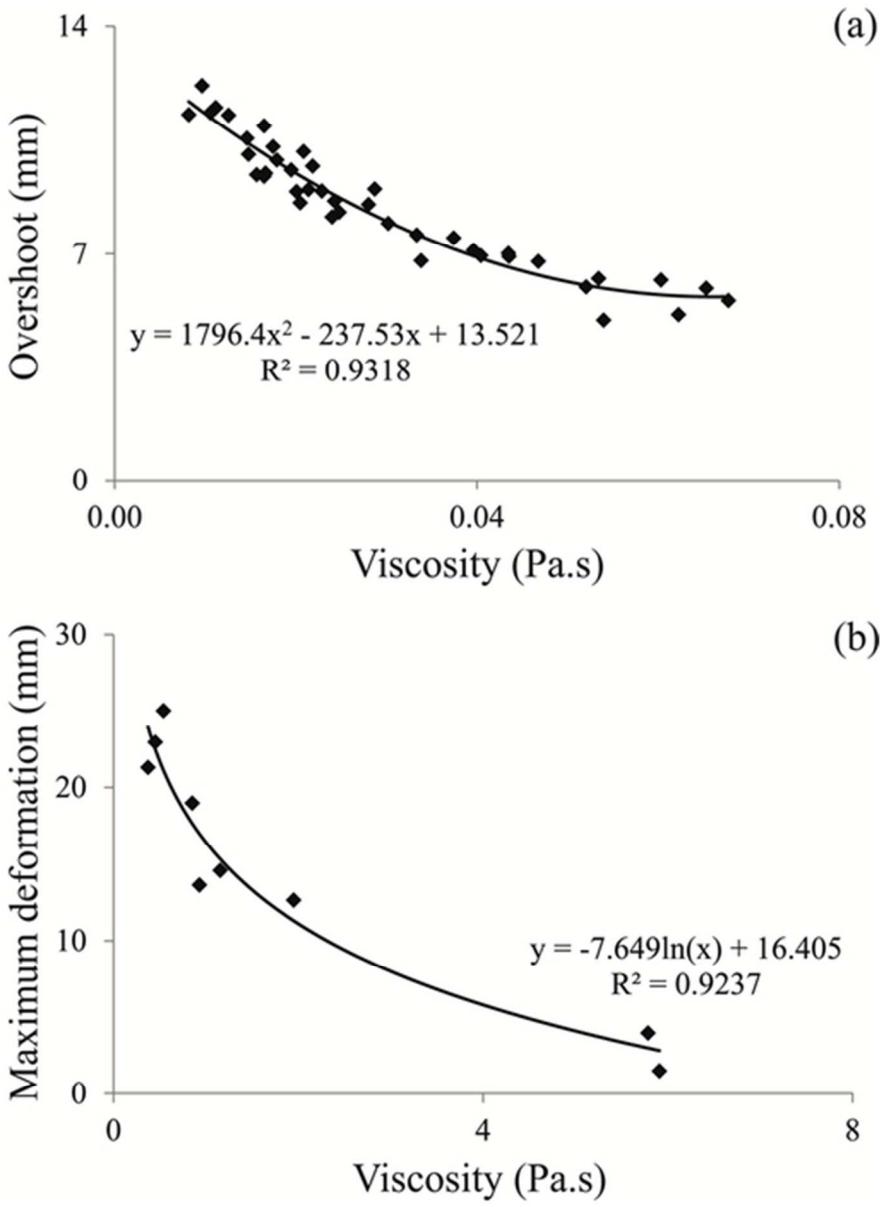

Figure 13: Correlation between the overshoot and the viscosity for twelve oil and fat types at different temperatures (a) and correlation between the maximum deformation and the viscosity for nine molten chocolate samples (b)
43x59mm (300 x 300 DPI)