# Use of Helical Ribbon Mixer for Measurement of Rheological Properties of Fruit Pulps

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**Abstract**

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Fruit pulps contain fine particles of the flesh of the original fruit that are suspended in the fruit juice. This suspension has a tendency to settling or separation during measurements of its rheological properties in the rotational rheometer with coaxial cylinders (especially if the greater gap is used). In this case the use of a mixer is convenient. The mixer can serve as a tool for measurement of rheological properties and at the same time it can prevent the settling and it is not sensitive to the occurrence of greater particles in the measured fluid. The helical ribbon mixer was used in this work for measurement of five samples of fruit pulp. The mixer was calibrated by the use of Newtonian fluid of known viscosity (honey). The radius of the inner cylinder of hypothetical rotational rheometer was predicted from the assumption that mixer and cylinder exhibit the same torque necessary for the rotation at the same rotational speed. The average shear rate in the mixed pulp was predicted by using the relation valid for power law fluids and rheometer with coaxial cylinders. The radius (where the average shear rate was calculated) was chosen by the requirement that the shear rate would be almost independent of changes in the flow behaviour index valid for measured pulps. Firstly the flow behaviour index was predicted as a slope of torque vs. rotational speed dependence in log-log co-ordinates. It was found that the flow behaviour index varies in the range 0.2–0.3. The radius was predicted from a graph where shear rates for 0.2 and 0.3 are the same. Then the average shear rates were calculated from rotational speeds for individual flow behaviour indexes. Rheological properties measured by using a mixer correspond to those measured with a rotational rheometer with coaxial cylinders satisfactorily only in the case that the creeping flow regime was kept in the mixed fluid. The fruit pulps are strongly non-Newtonian fluids with very low values of the flow behaviour index around 0.2.

**Keywords**: fruit pulps; rheological properties; method of mixer

The convenient consistency of fruit semi-product (fruit pulp) intended for baby foods produced without thickeners is a key assumption for achieving the desired consistency of the final product. The consistency is measured through viscosity or rheological properties. The real fruit pulp contains particles and fine fibres distributed in the fluid component of the suspension. The fluid component is basically composed of fruit saccharides and acids dissolved in water. The suspension has a tendency to settle. These factors can complicate the use of commercial rotational rheometers for the quality control of these fruit pulps. The Bostwick empirical consistency meter is currently used. This method needs to take sample from a batch and transport it to the laboratory. On the other hand, the modern methods of rotational rheometry enable to input the rheometer directly into a production line or to immerse the sensor into the container with raw material and predict the consistency in physical units and objectively. The use of a mixer has the advantage that it can be used even for hardly settling suspensions of coarse particles for which the system of coaxial cylinders cannot be used.

The aim of this work is to verify the method of rotational rheometry for fruit pulps using the non-standard geometry of a helical ribbon mixer and to compare the results received on standard geometry with coaxial cylinders. We also want to verify the calibration procedure published recently by CHOPLIN (2000).

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## MATERIAL AND METHODS

***Instruments***: Mixing experiments were carried out on rotational rheometer Rheotest 2, type RV 2 (Medingen, Germany). The temperature of samples was measured with digital thermometer Therm Pt100 (Ahlborn-Messtechnik, Germany). The thermostat Haake K20 and control unit Haake DC 50 were used for the tempering of samples. Acidity of samples was measured with pH-meter Radiometer (Copenhagen, Denmark).

***Samples***: The samples of fruit pulps were provided by a local producer of baby foods. Five samples were measured: peach pulp A, B, C and strawberry pulp A, B. Pulp samples differed in consistency, pH and refractometric dry matter. The composition of samples is given in Table 1.

Tab. I Composition of pulp samples and critical values of shear rates

| Pulp sample | pH | Refractometric dry matter (%) | Value of critical Re | Limit of shear rate ($s^{-1}$) |
|---|---|---|---|---|
| Peach A | 3.65 | 14.8 | 9.6 | 22.5 |
| Peach B | 3.78 | 9.5 | 5.6 | 12.2 |
| Peach C | 3.80 | 9.4 | 8.2 | 2.25 |
| Strawberry A | 3.32 | 5.6 | 9.1 | 9 |
| Strawberry B | 3.55 | 6.5 | 8.1 | 10.5 |

***Measurement of Rheological Properties of Pulps in a Rotational Rheometer***: Rheological properties of fruit pulps were measured by using a rotational rheometer Haake Rheostress RS-150. The software RheoWin Job Manager was used for experiment control and data export. Samples were tempered to the same temperature under which the mixing experiments were conducted. The system of coaxial cylinders was used, cup Z43 and cylinder Z41. Data on shear stress vs. shear rate were exported into the Microsoft Excel table processor and parameters $K'$ and $n$ of the power law model were calculated

$$\mu_z = K' . \dot{\gamma}^{n-1} \quad [1]$$

The model is written for the apparent viscosity $\mu_z$ as a function of the shear rate $\dot{\gamma}$, see e.g. ULBRECHT and MITSCHKA (1965). The relation [3] was used for correction of shear rates to the non-Newtonian behaviour. The radius of inner cylinder was input into this relation instead of the general radial co-ordinate $r$.

***Calibration of Helical Ribbon Mixer:*** The Newtonian fluid – honey was used for calibration of a helical ribbon mixer. The viscosity of honey (Rheostress RS-150) was measured at the same temperature as the mixing experiment (27°C). The viscosity of honey was µ = 8.994 Pa.s. The mixing experiment was conducted on rotational rheometer Rheotest 2. This instrument served as a tool for measuring the torque at a known rotational speed. The helical ribbon was mounted on the shaft of the rheometer instead of a standard cylinder. The helical ribbon agitated honey placed in the vessel with volume 2 litres and inner radius $R_e$ = 0.0725 m. The corresponding couples of the torque $M_k$ and rotational speed $N$ were input into equation [2] and the values of an equivalent radius of the cylinder of apparent rotational rheometer were calculated. The mean value $R_i$ = 0.04106 m has been predicted. Equation [2] can be developed from the torque equivalence for a mixer and cylinder of the apparent rotational rheometer rotating in the same fluid at the same rotational speed. The length $L$ of the cylinder was chosen the same as the length of the helical ribbon mixer, $L$ = 0.118 m.

$R_i$ was input into equation [3] and shear rates in the gap of apparent rheometer were calculated as a function of radius $r$ and flow behaviour index $n$. The proportionality constant $k_s$ can be directly calculated if the rotational speed of a mixer is chosen $N = 1\ s^{-1}$ (Fig. 1). It is apparent from this figure that the radius can be found where the shear rate dependences calculated for different flow behaviour indexes crossed over. It is the point where the shear rate and $k_s$ is nearly negligibly dependent on $n$. For example, this point is given by radius $r \cong 0.0505\ m$ for $n$ = 1 up to 0.5 (Fig. 1). It is also obvious from this figure that this point is not convenient for lower values of the flow behaviour indexes.

***Measurement of Rheological Properties of Pulps by a Mixer Method***: Pulps were mixed with helical ribbon mixer at room temperature and the torque at the given rotational speed was measured with rotational rheometer Rheotest 2. The same vessel was used for these experiments as that used previously for calibration with honey. By plotting the log $M_k$ vs. log $N$ the flow behaviour index can be predicted as a slope of the linear part of this graph. The values of flow behaviour indexes ranged between 0.2 – 0.3. In accordance with the method of CHOPLIN (2000) the radius $r$ = 0.0460 m was chosen where the shear rate dependences for $n$ = 0.2 and 0.3 crossed over at point $k_s$ = 20 (Fig. 1).

$$R_i = \frac{R_e}{\left[1 + \frac{4\pi N}{n}\left(\frac{2\pi \mu L R_e^2}{M_k}\right)^{1/n}\right]^{n/2}} \quad [2]$$

$$\dot{\gamma} = \frac{\frac{4\pi}{n}\left(\frac{R_i}{r}\right)^{2/n}}{1 - \left(\frac{R_i}{R_e}\right)^{2/n}} . N = k_s . N \quad [3]$$

Shear stress was then calculated from the equation:

$$\tau = \frac{M_K}{2.\pi.L.r^2} \quad [4]$$

This procedure provided only a rough agreement between the flow curves measured with rotational rheometer Rheostress and by using a mixer. The method had to be modified. The previously predicted radius $r = 0.0460$ m was used but the shear rates were recalculated. Individual values of $k_s$ were calculated for ranges of rotational speeds where the flow behaviour index was constant by inputting this value of $n$ into equation [3]. The reason for this modification was that the flow behaviour index was not constant for the total range of rotational speeds used in a given mixing experiment and individual pulp.

If the mixer is used for rheological measurements, the creeping flow regime should be kept during experiments. This can be achieved by keeping the Reynolds number under 10. Above this critical value the torque is not proportional any longer to the viscous forces. This limit is demonstrated by an unexpected unrealistic increase of the slope of dependence log $M_k$ vs. log $N$. After elimination of these experimental values the apparent viscosity was predicted from the equation:

$$\mu_z = \frac{\tau}{\dot{\gamma}} \quad [5]$$

## RESULTS AND DISCUSSION

### Measurement of Rheological Properties of Pulp in a Rotational Rheometer

Dependences of apparent viscosity on the corrected shear rate received from measurements on a rotational rheometer with coaxial cylinders Rheostress RS-150 were plotted for individual pulps in Figs. 2–6. It is obvious from these figures that the pulps behave as strongly non-Newtonian fluids with flow behaviour indexes between 0.2–0.3. The flow curves were measured for the same temperature for which the mixing experiment was conducted.

### Measurement of Rheological Properties of Pulp with a Mixer

Experimental torque values recorded as a function of rotational speeds were plotted into log $M_k$ vs. log $N$ graphs. The linear parts of these graphs were predicted together with ranges of rotational speeds. In these ranges the constant flow behaviour indexes were predicted as a slope by linear regression. For individual pulps, two ranges with different flow behaviour indexes were found regularly. The predicted flow behaviour index was input into equation [3] together with previously found variables $R_i$, $L$, and $r$ and the values of $k_s$ were predicted. The values of $k_s$ ranged

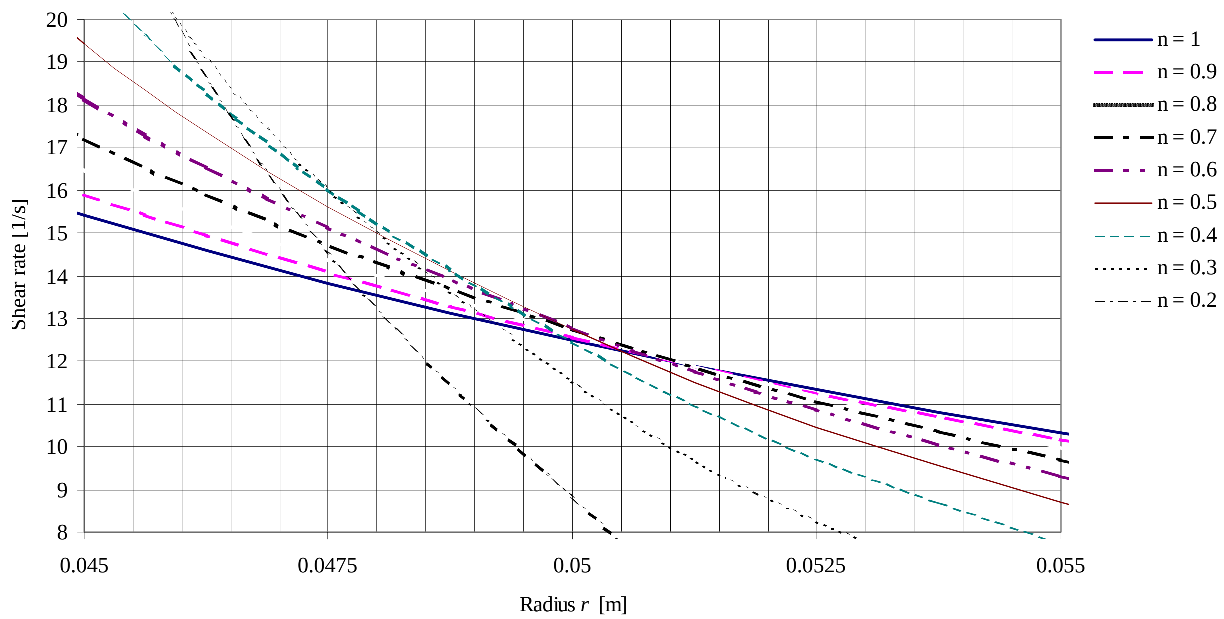


Fig. 1. Shear rate as a function of flow behaviour index $n$ and radius $r$ in the gap of hypotetical rheometer with coaxial cylinders for $N = 1\ s^{-1}$

between 15 to 28 (compare with the mean value of 20 predicted by strictly obeying the method of Choplin). The mean shear rates were predicted in this range of rotational speeds for which the flow behaviour index was constant and used for calculation of $k_s$. The corresponding mean shear stresses were calculated using equation [4]. This procedure was applied to all the data received during mixing experiments. The apparent viscosity as a function of mean shear rate was plotted for individual pulps in Figs. 2–6.

It is obvious from these figures that the flow curves measured by both methods are reasonably consistent. There are differences in the ranges where the same shear rates were not reached. Great differences were found in data measured at high rotational speeds of the mixer. It is due to the fact that the non-creeping regime of the flow of pulp started in the mixing vessel. The limit value of the Reynolds number is about 10. The lowest limit of apparent viscosity and the highest limit of shear rate were predicted and the values of these limits for the given pulps and mixer are shown in Table 1.

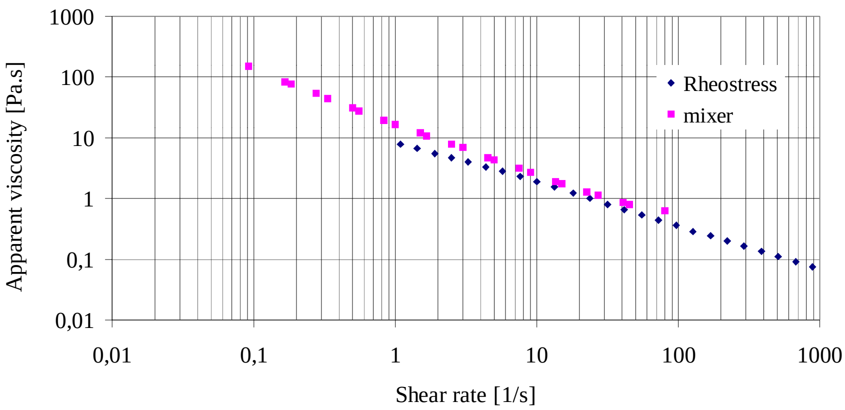


Fig. 2. Apparent viscosity vs. shear rate for peach pulp A, temperature 26.8°C

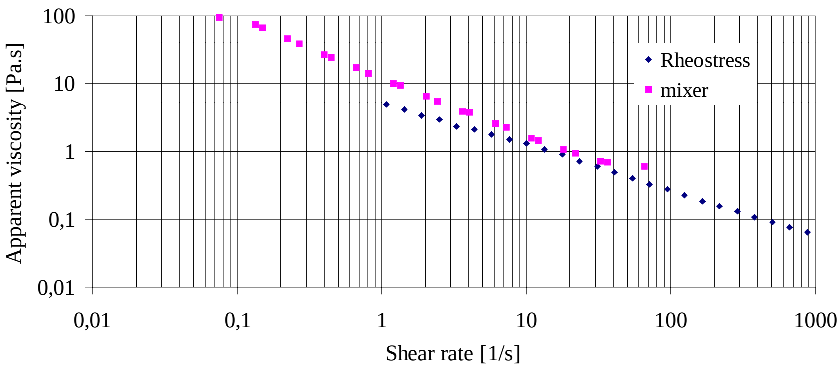


Fig. 3. Apparent viscosity vs. shear rate for peach pulp B, temperature 26.5°C

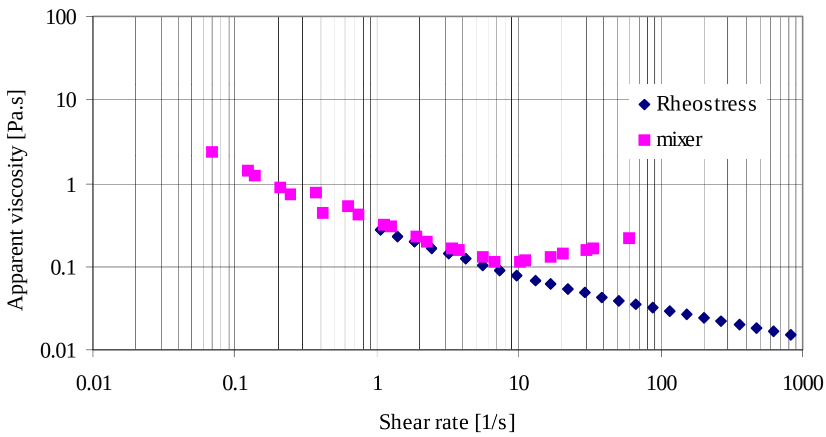


Fig. 4. Apparent viscosity vs. shear rate for peach pulp C, temperature 26.4°C

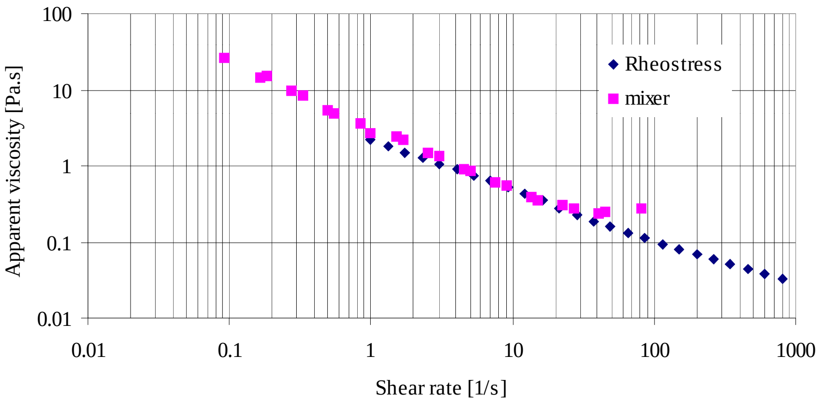


Fig. 5. Apparent viscosity vs. shear rate for strawberry pulp A, temperature 26.4°C

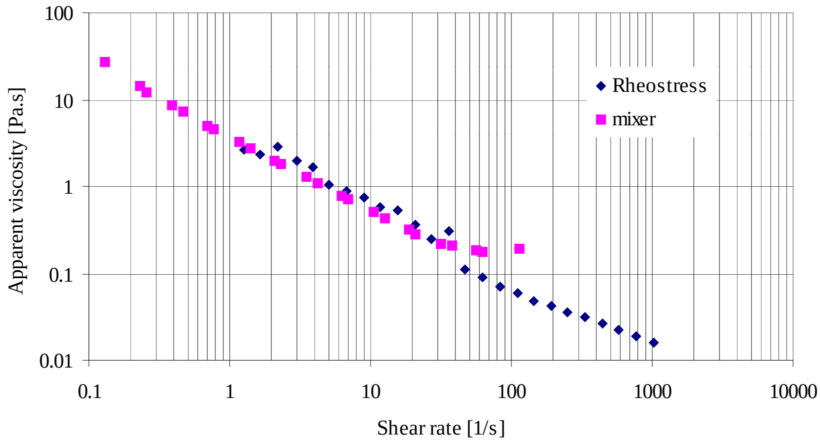


Fig. 6. Apparent viscosity vs. shear rate for strawberry pulp B, temperature 26.4°C

The flow curves predicted by both methods are very close in specific ranges of shear rates. In these ranges the flow behaviour indexes predicted by both methods are also very close.

Comparing the data we can deduce that Choplin's method can be used with modification. The best agreement was found if we predicted the local flow behaviour index and calculated the individual proportionality constant $k_s$ valid for the range of rotational speeds. The use of the mean proportionality constant for the whole range of shear rates can lead to great errors in shear rates esp. for a fluid with low value of flow behaviour index. The radius *r* can be deduced from Fig. 1 to find the point at which $k_s$ is as much as possible independent of the flow behaviour index in the expected range of this parameter.

## CONCLUSIONS

Rheological properties of five samples of fruit pulps were measured by using the method of rotational rheometer with coaxial cylinders and by the method of calibrated mixer. All the samples behaved as a strongly non-Newtonian fluid. The consistency of samples differed enormously. The highest consistency was found for peach pulp A with highest refractometric dry matter and the lowest consistency was found for peach pulp C. This pulp exhibited the highest value of flow behaviour index. The strawberry pulps exhibited higher consistency than peach pulp C in spite of the fact that they had much lower refractometric dry matter than peach pulp C. This pulp is suspected to be sweetened with saccharose which can cause that the relation between natural thickening substances (fibre and pectin) and dissolved sugars is unbalanced. This is confirmed by the higher value of flow behaviour index.

The method of flow curve measurement by using the calibrated mixer published by Choplin was verified. The creeping flow regime has to be kept during measurements. The method should be modified. The individual shear rate should be calculated for the local value of flow behaviour index valid for the given range of rotational speeds. The method of mixer esp. helical ribbon mixer is convenient for fruit pulps containing particles of fruit because the mixer prevents the settling. Contrary to previous methods (HOUŠKA 1980; ŠESTÁK *et al.* 1986), the described method of mixer calibration does not request any tedious experiments with sets of non-Newtonian calibration fluids. The prediction of an equivalent radius of the apparent rotational rheometer with coaxial cylinders can be done by means of calibration using one Newtonian fluid of known viscosity.

**Symbols**

| | | |
|---|---|---|
| $d$ | mixer diameter | [m] |
| $k_s$ | proportionality constant between shear rate and rotational speed | [–] |
| $K'$ | corrected consistency coefficient | [Pa $s^n$] |
| $L$ | mixer length | [m] |
| $M_k$ | torque | [N.m] |
| $n$ | flow behaviour index | [–] |
| $N$ | rotational speed | [$s^{-1}$] |
| $r$ | specific diameter | [m] |
| $R_i$ | equivalent radius of cylinder of apparent rheometer | [m] |
| $R_e$ | radius of the vessel used for mixing experiment | [m] |
| Re | Reynolds number for mixing (Re = $N.d^2\rho/\mu_z$) | [–] |
| $\dot{\gamma}$ | mean shear rate | [$s^{-1}$] |
| $\mu$ | dynamic viscosity | [Pa s] |
| $\mu_z$ | apparent viscosity | [Pa s] |
| $t$ | shear stress | [Pa] |
| $\rho$ | density | [$kg.m^{-3}$] |

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**Abstrakt**

NOVOTNÁ P., LANDFELD A., KÝHOS K., HOUŠKA M., STROHALM J. (2001): **Využití pásového míchadla k měření reologických vlastností ovocných dření.** Czech J. Food Sci., **19**: 148–153.

K měření reologických vlastností pěti vzorků dření bylo použito pásové míchadlo, které při měření dokáže zabránit sedimentaci částic a není citlivé na výskyt větších částic ve vzorku. Míchadlo bylo kalibrováno pomocí newtonské kapaliny o známé viskozitě (med) a byl určen ekvivalentní poloměr vnitřního válce rotačního reometru, který má stejný odpor jako testované míchadlo. Průměrná smyková rychlost v míchané dřeni byla odhadnuta pomocí vztahu platného pro mocninové kapaliny a reometr se souosými válci v takovém místě nádoby, kde je smyková rychlost nejméně závislá na indexu toku pro danou skupinu dření. Postup byl modifikován tak, aby se pro odhadnutý index toku ze závislosti krouticího momentu na otáčkách míchadla předem určila aktuální smyková rychlost ve zvoleném místě míchadla. Reologické vlastnosti dření proměřené míchadlem se poměrně dobře shodovaly s výsledky měření na rotačním reometru, pokud v míchadle byl zachován creepový režim proudění. Dřeně představují silně nenewtonskou kapalinu s velmi nízkým indexem toku okolo 0,2.



**Klíčová slova**: ovocné dřeně; reologické vlastnosti; metoda měření pomocí míchadla



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