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THE RHEOLOGICAL PROPERTIES OF REDCURRANT AND HIGHBUSH BLUEBERRY BERRIES

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ABSTRACT

The load values corresponding to the compressive strength of highbush blueberry and redcurrant fruits during the compression test between two rigid plates were measured. The changes of coefficient of elasticity and coefficient of viscosity values during the creep and the relaxation tests were studied in the selected interval of time, also direction of load application in relation to the longitudinal axis of fruit was considered. The creep and relaxation tests were carried out with the load of 40% of determined compressive strength of berries. To describe behavior of testing the material rheological standard, Maxwell and Kelvin models as well as experimental models were used. Comparatively small changes of parameter values of assumed empirical models were reported in the course of tests. It may be recognized as characteristic for the investigated material.

Introduction

Poland is the European leader in berry fruit production and a considerable growth of interest in highbush blueberry cultivation has been observed in recent years. It is influenced by the optimum climate - soil conditions, profitability of production as well as the dietary - wholesome benefits (Ścibisz and Mitek, 2002). The redcurrant and highbush blueberry fruits have high nutritious value due to potassium, phosphorus, calcium and magnesium contents. It contains large quantity of vitamin A. Moreover, it was confirmed that they contain components with anti-cancer as well as anti-oxidant properties (Łata et al., 2007).

Morris (1983) reported that marketable fruit of machine-harvested highbush blueberries was from 4 to 44% less than that of the hand-harvested blueberries. Machine-harvested fruits in ripe category were 4 to 32% softer than hand-harvested fruits. Sorting and grading machine-harvested fruit on a commercial cleaning line further soften the berries and cause more decay in storage. So far, investigations on the texture and different physical properties of high blueberry and currant berries were carried out (Antonio et al., 2009; Chiabrando et al., 2009; Ochmian et al., 2014; Petrisor et al., 2013). In the available literature there is only scant information on the subject results of rheological investigations of redcurrant or blueberry whole fruits.

Determination of rheological features can be significant for the qualification course and the range of fruits deformation, particularly during transportation and storage.

Gołacki et al. (2005) stated that the compressive and relaxation tests generally are used to obtain information on the viscoelastic properties of fruit and vegetables. Bohdziewicz and Czachor (2005) stated that extension or shortening of the duration of the creep and relaxation tests may result in change of mutual relations of coefficients of elasticity and the coefficients of viscosity value of the tested material. The relations of stress changes as a function of relaxation test time can be described by standard (Rao, 2007) four-parameter Maxwell's model equation:

$$\sigma(t) = a_1 \cdot e^{-b_1 t} + c_1 \cdot e^{-d_1 t} \tag{1}$$

However, the course of changes of deformation during creep test by the four-parameter Kelvin's model equation was as follows:

$$\varepsilon(t) = a_2 \cdot (1 - e^{-b_2 t}) + c_2 \cdot (1 - e^{-d_2 t}) \tag{2}$$

In both equations: $\sigma(t)$– stress (MPa); $\varepsilon(t)$– strain (-); *a, b, c, d,*– equation parameters to calculation of coefficients E and η; t – test time.

The measuring experiments conducted by Bohdziewicz and Grzemski (2012) showed that the better adjustment to the course σ (t) relation has the empirical equation recorded as:

$$\sigma(t) = a_3 \cdot e^{-b_3 \cdot t} + c_3 \cdot [(1 + d \cdot t^e)^{-1}] \tag{3}$$

However, for description of ε (t) the course the empirical formula was used:

$$\varepsilon(t) = a_4 \cdot (1 - e^{-b_4 \cdot t}) + c_4 \cdot [1 - (1 + d \cdot t^e)^{-1}] \tag{4}$$

In both equations: *a, b, c, d* – equation parameters to calculation of coefficients E_1, E_d and η *d, e,* – equation ratios, t – test time.

Objective, object and methodology

The objective of the undertaken investigations was delimitation of the rheological properties of berry fruits based on the answers registered in the conditions of relaxation and creep tests. Berries of highbush blueberry Bluecrop var. and the redcurrant Rosetta var. grown on industrial scale in the Lower Silesia region bought on the fruit farm after gathering directly were the object of investigations. The sorted material for the conducted tests was chosen in relation to the fruit shape and size.

Before commencement of rheological tests, redcurrant as well as blueberry fruits were weighed with precision up to 10^{-4} g with the use of measurement scale type WPA 60C. The diameters of spherically shaped fruits were measured in three perpendicular directions in relation to the longitudinal axis of berry with precision up to 10^{-2} mm using a digital caliper. The measurement results enable calculation of the conventional density of individual fruits (Lozano, 2006). After tests, moisture of material was determined by the standard dry method provided in the temperature of 105ºC by 24 hours.

Ten iterations of compressive tests of whole fruit between two rigid plates were carried out in axial and radial directions of load on Instron type 5566 machine, the speed of measurement head with the range of 0.1 kN was $5 \cdot 10^{-5}$ m·s^{-1}. Rheological tests were carried out at the load not exceeding 40% break force corresponding to the strength measured based on the compression tests. These investigations were carried out in both directions of load application and were interrupted after 1200 seconds time course.

Results of investigations

The results of measurements of the physical properties and break forces of the investigated material were introduced in table 1.

Table 1.
Comparison of average values of chosen physical properties of investigated material

Material	Mass (SD) (g)	Moisture (SD) (%)	Density (SD) (kg·m^{-3})	Axial force F_{max}, (N)	Radial force F_{max}, (N)
Blueberry	1.92 (0.02)	84% (1%)	1331 (27)	7.39 (0.84)	5.38 (0.56)
Redcurrant	1.71 (0.04)	88% (3%)	1370 (55)	6.12 (0.75)	4.09 (0.39)

SD - Standard deviation

The relaxation test was conducted with three iterations of measurement for two groups of size selection. The four-parameter Maxwell's model allows determination of the values of coefficients of elasticity E_1 and E_2 as well as the coefficients of viscosity η_1 and η_2. These values were calculated independently for four interval time θ. The set of average values of parameters calculated based on equation (1) are presented in tables 2 and 3.

Table 2.
Comparison of average values of parameters of Maxwell's model for different time scales; the relaxation test in axial direction

Material	Interval of time θ (s)	Four-parameter Maxwell model				
		E_1 (MPa)	η_1 (MPa·s)	E_2 (MPa)	η_2 (MPa·s)	R^2
Redcurrant	θ_1 (0-300)	0.40	5.5	0.15	204	0.975
	θ_2 (0-600)	0.46	13.2	0.16	417	0.972
	θ_3 (0-900)	0.41	17.7	0.17	637	0.972
	θ_4 (0-1200)	0.41	23.5	0.18	837	0.973
Blueberry	θ_1 (0-300)	0.34	6.7	0.18	179	0.984
	θ_2 (0-600)	0.35	11.6	0.19	360	0.982
	θ_3 (0-900)	0.34	15.7	0.20	524	0.982
	θ_4 (0-1200)	0.34	19.6	0.21	674	0.982

Table 3.
Comparison of average values of parameters of Maxwell's model for different time scales; the relaxation test in radial direction

Material	Interval of time θ (s)	Four-parameter Maxwell model				
		E_1 (MPa)	η_1 (MPa·s)	E_2 (MPa)	η_2 (MPa·s)	R^2
Redcurrant	θ_1 (0-300)	0.25	2.9	0.23	71	0.983
	θ_2 (0-600)	0.25	5.0	0.26	113	0.984
	θ_3 (0-900)	0.25	5.9	0.27	130	0.987
	θ_4 (0-1200)	0.25	5.8	0.27	129	0.989
Blueberry	θ_1 (0-300)	0.24	8.9	0.20	87	0.978
	θ_2 (0-600)	0.17	12.3	0.26	142	0.987
	θ_3 (0-900)	0.17	15.4	0.27	215	0.989
	θ_4 (0-1200)	0.17	18.7	0.28	401	0.991

It may be noticed that there are less significant essential changes of coefficients of elasticity E_1 and E_2 values both for redcurrant as well as blueberry fruits in longer time ranges. The values of coefficients E_1 are smaller at the load in radial direction; however values of coefficients E_2 are respectively higher. The values of coefficients of viscosity η are different in relation to the test time as well as direction of load application. In case of redcurrant, the value of parameter η_2 is four times higher for axial direction than for the perpendicular direction. This differentiation in case of blueberry is not so clear. Along with the extension of the observation time the values of coefficient of viscosity increase. In case of the axial direction of load for redcurrant berries almost a fourfold growth of this values and threefold for blueberry can be reported.

For better adjustment of the empirical model (equation 3) for studied course in tables 4 and 5 the values of parameters of this model within 1200 seconds are set.

Table 4.
Comparison of average values of empirical model parameters in different time scales, the relaxation test in axial direction

Material	Interval of time θ (s)	Empirical model					
		E_1 (MPa)	η_1 (GPa·s)	E_d (MPa)	Ratio a (-)	Ratio b (-)	R^2
Redcurrant	θ_1 (0-300)	0.22	1.00	0.18	0.28	0.46	0.999
	θ_2 (0-600)	0.26	2.56	0.16	0.26	0.42	0.999
	θ_3 (0-900)	0.28	3.94	0.15	0.26	0.40	0.999
	θ_4 (0-1200)	0.28	4.16	0.15	0.26	0.40	0.999
Blueberry	θ_1 (0-300)	0.34	1.94	0.14	0.24	0.47	0.999
	θ_2 (0-600)	0.36	2.58	0.14	0.24	0.46	0.999
	θ_3 (0-900)	0.36	2.61	0.14	0.24	0.46	0.999
	θ_4 (0-1200)	0.37	2.74	0.14	0.24	0.46	0.999

Table 5.
Comparison of average values of empirical model parameters in different time scales, the relaxation test in radial direction

Material	Interval of time θ (s)	Empirical model					
		E_1 (MPa)	η_1 (GPa·s)	E_d (MPa)	Ratio a (-)	Ratio b (-)	R^2
Redcurrant	θ_1 (0-300)	0.67	0.19	0.12	0.29	0.50	0.998
	θ_2 (0-600)	0.55	0.19	0.12	0.29	0.54	0.999
	θ_3 (0-900)	0.43	0.18	0.13	0.26	0.62	0.999
	θ_4 (0-1200)	0.35	0.16	0.15	0.21	0.76	0.999
Blueberry	θ_1 (0-300)	0.34	0.69	0.08	0.21	0.47	0.998
	θ_2 (0-600)	0.24	1.56	0.07	0.20	0.44	0.998
	θ_3 (0-900)	0.22	1.88	0.07	0.20	0.43	0.998
	θ_4 (0-1200)	0.22	1.97	0.07	0.20	0.43	0.998

With time of relaxation tests, coefficient of elasticity E_d values do not show significant differences regardless the load application direction. Parameter E_1 has a higher value in tests carried out in radial direction. The largest differentiation of the value of coefficient of viscosity η_1 in relation to the test time in case of redcurrant berries for axial direction of load application. Slight changes of the coefficients of elasticity values as well as the coefficient of viscosity for longer intervals of time are noticeable. For blueberry fruits applying the load in radial direction results with a threefold change of the coefficient of viscosity value.

The creep test was carried out with three iterations of measurements for two groups. A comparison of average values of Kelvin's model parameters received on the basis of equation 2 are presented in tables 6 and 7.

Table 6.
Comparison of average values of parameters of Kelvin's model for different time scales; the creep test in axial direction

Material	Interval of time θ (s)	Four-parameter Kelvin model				
		E_1 (MPa)	η_1 (MPa·s)	E_2 (MPa)	η_2 (MPa·s)	R^2
Redcurrant	θ_1 (0-300)	2.38	27.2	1.42	180	0.999
	θ_2 (0-600)	1.81	31.3	1.41	320	0.998
	θ_3 (0-900)	1.57	34.8	1.41	465	0.997
	θ_4 (0-1200)	1.46	38.0	1.39	625	0.996
Blueberry	θ_1 (0-300)	3.05	28.3	1.26	188	0.999
	θ_2 (0-600)	2.33	34.9	1.192	288	0.998
	θ_3 (0-900)	1.90	42.4	1.14	419	0.997
	θ_4 (0-1200)	1.68	48.1	1.11	543	0.997

Table 7.
Comparison of average values of parameters of Kelvin's model for different time scales; the creep test in radial direction

Material	Interval of time θ (s)	Four-parameter Kelvin model				
		E_1 (MPa)	η_1 (MPa·s)	E_2 (MPa)	η_2 (MPa·s)	R^2
Redcurrant	θ_1 (0-300)	2.01	17.6	0.61	156	0.999
	θ_2 (0-600)	1.76	20.4	0.51	193	0.998
	θ_3 (0-900)	1.71	21.2	0.50	200	0.997
	θ_4 (0-1200)	1.66	22.2	0.50	208	0.999
Blueberry	θ_1 (0-300)	2.16	19.1	0.95	93	0.999
	θ_2 (0-600)	2.11	24.6	0.85	157	0.998
	θ_3 (0-900)	2.09	27.2	0.84	226	0.997
	θ_4 (0-1200)	1.98	30.0	0.84	287	0.997

It can be observed that at the load application in axial direction the coefficient of elasticity E_1 decreased by half of the value in the test time course as well as E_2 did not undergo any material changes. The values of the coefficient of viscosity increase. It concerns both redcurrant and blueberry fruits. Disproportion of coefficients η values in case of blueberry for radial direction of load in comparison to axial direction is noticeable. It results from the minimum outflow of liquid from investigated berries during the creep test, even at the load on level of 40% value of break strength of fruits. Significant changes of value of coefficients of viscosity η_1 and η_2 are observed with relation to time which proves weak reflection of properties of the tested material.

To describe the course of the creep test the empirical model worked out on the basis of equation (4) was also used. The results of calculations of parameters of the received model were set in tables 8 and 9.

Table 8.
Comparison of average values of empirical model parameters in different time scales, the creep test in axial direction

Material	Interval of time θ (s)	Empirical model					
		E_1 (MPa)	η_1 (GPa·s)	E_d (MPa)	Parameter *a* (-)	Parameter *b* (-)	R^2
Redcurrant	θ_1 (0-300)	3.04	1.20	0.94	0.06	0.76	0.999
	θ_2 (0-600)	2.89	1.89	0.87	0.06	0.73	0.999
	θ_3 (0-900)	2.56	2.86	0.81	0.06	0.72	0.999
	θ_4 (0-1200)	2.42	3.29	0.79	0.06	0.71	0.999
Blueberry	θ_1 (0-300)	1.54	1.03	0.73	0.06	0.62	0.999
	θ_2 (0-600)	2.07	1.51	0.84	0.06	0.63	0.999
	θ_3 (0-900)	2.39	2.56	0.72	0.05	0.63	0.999
	θ_4 (0-1200)	2.25	2.77	0.71	0.05	0.63	0.999

Table 9.
Comparison of average values of empirical model parameters in different time scales, the creep test in radial direction

Material	Interval of time θ (s)	Empirical model					
		E_1 (MPa)	η_1 (GPa·s)	E_d (MPa)	Parameter *a* (-)	Parameter *b* (-)	R^2
Redcurrant	θ_1 (0-300)	0.49	0.23	1.10	0.14	0.70	0.999
	θ_2 (0-600)	0.53	0.23	1.11	0.14	0.69	0.999
	θ_3 (0-900)	0.53	0.23	1.33	0.14	0.81	0.999
	θ_4 (0-1200)	0.53	0.24	1.30	0.14	0.79	0.999
Blueberry	θ_1 (0-300)	0.88	0.63	1.06	0.15	0.74	0.999
	θ_2 (0-600)	0.93	0.66	1.04	0.14	0.70	0.999
	θ_3 (0-900)	0.95	0.68	1.04	0.14	0.68	0.999
	θ_4 (0-1200)	0.94	0.67	1.04	0.14	0.73	0.999

Disproportion of coefficients of elasticity E_1 values in relation to the creep test time is noticeable. In case of redcurrant for both load application direction it is almost sixfold diversification. This concerns also the coefficient of viscosity η_1 values. As in the standard model the insignificant outflow liquid from the blueberry's fruits in course of test time in radial direction of load is effective with differentiation of results calculation of empirical model parameters for both directions of load.

Conclusions

1. The rheological properties of similarly sized berry fruits are not identical with relation to the load application. In course of relaxation tests time changes of the parameters values of rheological models with regard to exocarps of blueberry fruits are higher than respectively for redcurrants berries.
2. Characteristic for empirical models are comparatively small changes of values of coefficients of elasticity according to the relaxation tests time. Changes of the value of coefficients of viscosity η of these models depend on time as well as on the direction of load application. In case of redcurrant the value of coefficient of viscosity is four times higher in axial direction of load than in the perpendicular direction. With extension of the observation time the values of the coefficient of viscosity increase. A fourfold increase of this value may be observed for the axial direction in case of redcurrant berries and a threefold for blueberry fruits.
3. Based on the creep test it was found out that there are comparatively small changes of values of the empirical model parameters relation to the load application direction and the test time. Disproportion of the values of coefficients η is noticeable in case of blueberry fruits for radial direction resulting from liquid outflow from the investigated berries.
4. Changes of the parameters values of standard models are not explicit. The increase of the coefficient of elasticity E_1 value is accompanied by the decrease or growth of E_2 value. Similarly it concerns the values of the coefficients of viscosity. It does not result from physical changes in the object of investigations but mathematical adjustment of two model courses to the real course.

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WŁAŚCIWOŚCI REOLOGICZNE OWOCÓW BORÓWKI WYSOKIEJ I PORZECZKI CZERWONEJ

Streszczenie. Wyznaczano wartości obciążenia odpowiadające wytrzymałości doraźnej podczas testu ściskania pomiędzy dwiema sztywnymi płytami owoców borówki wysokiej i porzeczki czerwonej. Badano zmiany wartości współczynnika sprężystości i współczynnika lepkości w wybranych przedziałach czasowych podczas testu pełzania i relaksacji naprężeń, uwzględniono kierunek przyłożenia obciążenia w stosunku do osi podłużnej owocu. Testy pełzania i relaksacji naprężeń realizowano przy obciążeniu odpowiadającym wartości 40% wyznaczonej wytrzymałości doraźnej. Wykorzystano standardowe oraz eksperymentalne modele reologiczne. Stwierdzono stosunkowo niewielkie zmiany wartości parametrów przyjętych modeli empirycznych z upływem czasu realizacji testu. Na tej podstawie można uznać je jako charakterystyczne dla badanego materiału.

Słowa kluczowe: borówka wysoka, porzeczka, pełzanie, relaksacja naprężeń, modele reologiczne