Influence of maturity stages and variety on viscoelastic properties and mechanical toughness of the strawberries

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Abstract

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Introduction. This study aims to determine the influence of maturity stages and variety on the strawberries viscoelastic properties and to evaluate their mechanical toughness.

Materials and methods. The fresh strawberry samples (*Vibrant*, *Elsanta* and *Magic* variety) were subjected to a creep test and the Burger model with four Kelvin Voigt elements was used to determine the viscoelastic parameters. The strawberry samples were divided on three maturity stages: almost ripe (S1), ripe (S2) and overripe (S3).

Results and discussion. The strawberries samples were analyzed in terms of moisture content, soluble substances concentration, pH and total acidity. The moisture content ranged between 87.38 and 89.67%, the overripe maturity stage (S3) showing higher values of moisture compared to nearly ripe ones (S1), $p < 0.05$. The highest concentration of soluble substances was recorded by *Elsanta* variety overripe maturity stage and followed by *Magic* (11.91) and *Vibrant* (11.57) varieties.

The instantaneous elastic strain of strawberries ranged between 1.057–3.135 mm and the retardation time, which is correlated with storage period, varies from 10.92 to 140.83 s. The Pearson correlation matrix between physicochemical (moisture content, Brix concentration, pH and total acidity) and viscoelastic parameters (retarded and instantaneous elastic strain, retardation time, viscous strain, creep strain and area under the creep curves) highlighted a significant positive correlation between retarded elastic strain (ϵ_2) and the creep strain ($p < 0.01$).

Conclusions. The *Vibrant* strawberry variety had the highest resistance to mechanical impact and also a high mechanical resistance to compression due to the fact that showed the lowest values of instantaneous and retarded elastic strain

Introduction

Strawberries (*Fragaria x ananassa* Duch.) are fragile, nonclimacteric fruits, consumed by worldwide people due to the nutrients presence (dietary fibers, vitamin C, sugars, organic acids and minerals), bioactive compounds (phenols, anthocyanins) and for their organoleptic characteristics including texture properties [1, 2].

According to Kim, 2013, [3] strawberries have an initial growing and enlarging stage followed by a maturation stage. The ripening process of strawberries stops when the fruits are harvested, this biochemical process being a very complex one influenced by the hormones, pigments synthesis, the sugars metabolism and their action; thus the ripening process changes the fruits color, aroma, flavor and texture [4, 5].

Over the years a large number of strawberry varieties have been created by the breeding programs over the world, in Romania the most cultivated varieties were: *Premial*, *Elsanta*, *Magic*, *Senga Sengana*, *Elegance*, *Real*, *Elgnore*, *Darselect*; on an area of about 2,500 ha and with a production of approximately 9 t/ha [6].

A major aspect of strawberry fruits it is represented by their firmness, which is the result of both the fruit pulp firmness and fruit skin strength; the information about strawberries mechanical properties being of great importance. The firmness measurement of strawberries is valuable in quality assurance, ripening evaluation, toughness damage evaluation during handling or differences between varieties [7].

The fruits mechanical properties (firmness or toughness) are measured most commonly by various types of penetrometers (Magness Taylor test), which are less acceptable for softer fruits such as strawberries [8].

A relatively simple test for viscoelastic properties evaluation of food products and to obtain a rheological model is the creep test, which implies a constant stress application on a sample and the deformation or strain is measured as a function of time [9, 10].

The viscoelastic properties measurements by rheological tests were applied for: apples [11], frankfurters [12], potato [13], bread dough [14] and gels [15]. To date no other study related to the viscoelastic properties of strawberries has been reported.

Therefore, the objective of this study is to evaluate the viscoelastic properties and quality characteristics of three strawberry varieties based on compression creep test and Burger mechanical model.

Materials and methods

Materials. The fresh strawberry samples were purchased from a local producer (Suceava, Romania) and they are of the *Vibrant*, *Elsanta* and *Magic* variety. Each strawberry variety was divided on three maturity stages: almost ripe (S1), ripe (S2) and overripe (S3), having about the same weight (18 ± 0.35 g) and volume (20 ± 0.55 cm³).

Physicochemical parameters. The soluble substances concentration (°Brix) was measured with a Leica Mark II Plus refractometer, the moisture content was performed by oven method [16], the pH was measured using a Hach pH-meter (HQ11d), [17] and total acidity were determined too and express as cm³NaOH/100g sample [18].

Texture properties measurement. For strawberries texture properties (toughness) evaluation a creep test was performed using an electronic device (Mitutoyo, USA), [19], the stress force was held constant at 200 g and the stress time was 1200 s. The compression probe

was flat with a diameter of 70 mm, larger than the cross-sectional area of the sample, thus eliminating the shear stress effect [20].

To determine the viscoelastic properties of strawberries samples, the strain versus time data (creep curves) were interpreted using Burger model with 4 KelvinVoigt elements (eq.1).

$$\varepsilon(t) = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = \frac{\sigma_0}{G_0} + \frac{\sigma_0}{G_1} \cdot \left(1 - \exp \frac{-t}{\lambda_{ret}}\right) + \frac{\sigma_0 \cdot t}{\mu_0} \quad (1)$$

where $\varepsilon(t)$ represents the strain at retardation time (t), ε_1 – the instantaneous elastic strain, ε_2 – the retarded elastic strain, ε_3 – viscous strain, G_0 – the instantaneous elastic modulus (Pa); G_1 – the retarded elastic modulus (Pa); λ_{ret} – the retardation time for the Kelvin part of the model (s); μ_0 – the Newtonian viscosity of the free dashpot (Pa s) and σ_0 represents the constant stress (Pa), [21, 22].

The Burger model shown in Fig.1 is the series combination of a Kelvin-Voigt and Maxwell elements, dividing the creep curve into three parts: instantaneous deformation (Maxwell spring), viscoelastic deformation (Kelvin element) and viscous deformation (Maxwell dashpot) [11].

Figure 1. Burger model

As a measure of the Burger mechanical model's fit to the experimental data the coefficient of determination (R^2) and the absolute average deviation (AAD) were calculated by the following equations [23]:

$$R^2 = 1 - \frac{\sum_{i=1}^n (Y_{CAL} - Y_{EXP})^2}{\sum_{i=1}^n (Y_{EXP} - Y_{MEDIU})^2} \quad (2)$$

$$AAD = \frac{1}{T} \cdot \sum_{i=1}^n \left| \frac{Y_{EXP} - Y_{CAL}}{Y_{EXP}} \right| \cdot 100 \quad (3)$$

where Y_{EXP} and Y_{CAL} are the experimental and calculated values data and T is the number of the experimental run [24].

Statistical analysis. The results were subjected to one factor analysis of variance (ANOVA) by STATGRAPHICS CENTURION XVI, the statistical significance being set at $\alpha = 0.05$. The Burger model predicted data was obtained by nonlinear regression analysis. Pearson correlation was performed by SPSS (SPSS Inc., Chicago, IL, USA) and Principal Component Analysis (PCA) by UNSCRAMBLER 9.7 (Trial Version).

Results and discussion

Physicochemical properties

In Table 1 are presented the ANOVA results of physicochemical parameters of strawberry samples. The *Vibrant*, *Elsanta* and *Magic* strawberries varieties were analyzed in terms of moisture content, soluble substances concentration, pH and total acidity. The strawberries moisture content ranged between 87.38 and 89.67%, the overripe maturity stage showing higher values of moisture compared to nearly ripe ones; the results of one factor analysis of variance ANOVA showed that the differences is statically significant at $p < 0.05$. The concentration of soluble substances express as ° Brix varies from 8.11 (almost ripe) to 13.89 (overripe), the highest concentration being recorded by *Elsanta* variety overripe maturity stage and followed by *Magic* (11.91) and *Vibrant* (11.57) varieties. The moisture and soluble substances contents being similar to those reported in other studies [25, 26].

Table 1
ANOVA physicochemical parameters of strawberry samples

Strawberry samples – mean (SD)		Moisture [%]	° Brix concentration	pH	Total Acidity [cm ³ NaOH/100g]
<i>Vibrant</i>	Almost ripe	87.51 ^b (0.34)	8.11 ^a (0.34)	3.88 ^a (0.09)	10.65 ^a (0.32)
	Ripe	88.96 ^{ab} (0.41)	9.21 ^a (0.12)	3.90 ^a (0.08)	10.59 ^{ab} (0.25)
	Over ripe	89.67 ^a (0.25)	11.57 ^b (0.30)	4.08 ^a (0.05)	9.37 ^b (0.54)
<i>Elsanta</i>	Almost ripe	88.63 ^b (0.31)	8.95 ^a (0.12)	3.80 ^a (0.08)	11.01 ^a (0.15)
	Ripe	89.01 ^{ab} (0.21)	9.93 ^a (0.10)	3.85 ^a (0.11)	10.78 ^{ab} (0.19)
	Overripe	89.58 ^a (0.22)	13.89 ^b (0.20)	3.99 ^a (0.05)	9.29 ^b (0.21)
<i>Magic</i>	Almost ripe	87.38 ^b (0.11)	8.89 ^a (0.11)	3.92 ^a (0.05)	10.51 ^a (0.88)
	Ripe	87.90 ^{ab} (0.20)	9.23 ^a (0.10)	4.10 ^a (0.06)	9.01 ^{ab} (0.10)
	Overripe	89.28 ^a (0.09)	11.91 ^b (0.21)	4.01 ^a (0.02)	9.32 ^b (0.56)
F-Ratio		6.93	17.50	2.46	4.37
P – value		0.027	0.003	0.166	0.067

Note: NS – not significant ($p > 0.05$), * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; Different lowercase letters in a column show significant differences between the groups ($p < 0.05$).

One way ANOVA analysis highlighted the soluble substances difference between the maturity stages of strawberries samples at a level of $p < 0.01$. The strawberries pH values were close to each other (3.80–4.10); the statistical differences being insignificant ($p > 0.05$). Total acidity content measurement is important in strawberries quality evaluation since less acidic strawberries are preferred to be consumed fresh, while more acidic strawberries are processed by food industry [27].

The total acidity of *Vibrant*, *Elsanta* and *Magic* varieties was between 9.29–11.01 $\text{cm}^3\text{NaOH}/100\text{g}$, decreasing with the strawberries ripening process; which is in agreement with the study of *da Silva Pinto 2008*, [28], who sustain also that the fruit acid content is consumed in the respiratory process.

Texture properties measurement

Mechanical properties evaluation is very important especially when it comes to fragile perishable food products susceptible to mechanical damage and it is also of great importance in measuring their viscoelastic properties. Strawberries are highly perishable fruits with a short shelf life due to the fact that they are predisposed to microbiological contamination and mechanical damage during harvesting, transport and storage; the fruit's resistance evaluation to mechanical shocks representing a very important aspect for both producers and consumers.

Figure 2 (a, b and c) presents the *Vibrant*, *Elsanta* and *Magic* strawberries toughness evaluation to mechanical stress by creep test and as we can see the strawberries deformation resistance depends on the fruit variety and also of the maturity stages. The most toughness strawberries to compression stress belong to the *Vibrant* variety followed by *Elsanta* and *Magic*. The creep curves of analyzed strawberries can be also characterized by two very important determinants – the strain and the area under the curve (W), this values being presented in Table 2.

The strawberries strain range from 1.96 mm to 6.62 mm, the greatest deformation being recorded by the *Magic* variety (5.79–6.62) which shows also the greatest area under the curve (75.65–81.45). In contrast with *Magic* variety, which shows a low resistance to deformation, the *Vibrant* variety strawberries have a greater resistance to deformation (1.96–2.67), being more resistant to mechanical shocks during the harvest and postharvest handling like sorting, packing, cleaning or to transport. As regarding the maturity stages, the overripe strawberries are softer than the ripe ones, the loss of deformation resistance being due to the ripening process, when the fruits turn redder, accumulate more sugars, the moisture content increases and lose some of their firmness [3].

Strawberries viscoelastic parameters prediction using Burger model

Another important aspect stated by *Vergara 2018*, [27] is that smaller strawberries (third category) have a higher resistance to deformation due to a more compact cellular arrangement. Also in Table 2 are presented the mathematical equations of Burger model, which were applied to describe the viscoelastic properties of analyzed strawberry samples; Figure 2 shows the Burger model's fit (predicted data) to the experimental data and it can be observed that the four elements mechanical model can be successfully used to predict the viscoelastic properties of strawberries samples.

Figure 2. Creep curves of strawberry samples – experimental vs. predicted data:
a – Vibrant, b – Elsanta, c – Magic.
 S1 – almost ripe, S2 – ripe, S3 – overripe.

Table 2

Equations of Burger mechanical model and the strawberries creep curves characteristics

Sample		Burger model with four Kelvin Voigt elements	R ²	AAD	Strain [mm]	W [mm·min]
Vibrant	S1	$\gamma = 1.057 + 0.483 \cdot \left(1 - \exp \frac{-t}{98.649}\right) + \frac{t}{2897.678}$	0.952	1.75	1.96	26.58
	S2	$\gamma = 1.374 + 0.588 \cdot \left(1 - \exp \frac{-t}{10.920}\right) + \frac{t}{2906.185}$	0.926	2.35	2.36	35.78
	S3	$\gamma = 1.647 + 0.738 \cdot \left(1 - \exp \frac{-t}{52.898}\right) + \frac{t}{4057.171}$	0.943	2.47	2.67	40.36
Elsanta	S1	$\gamma = 1.108 + 2.473 \cdot \left(1 - \exp \frac{-t}{120.032}\right) + \frac{t}{2025.271}$	0.982	2.95	4.18	50.11
	S2	$\gamma = 1.248 + 2.476 \cdot \left(1 - \exp \frac{-t}{97.301}\right) + \frac{t}{1112.259}$	0.983	2.61	4.82	56.96
	S3	$\gamma = 1.321 + 3.113 \cdot \left(1 - \exp \frac{-t}{56.056}\right) + \frac{t}{1336.073}$	0.971	4.26	5.30	66.60
Magic	S1	$\gamma = 3.029 + 2.052 \cdot \left(1 - \exp \frac{-t}{140.830}\right) + \frac{t}{2290.884}$	0.965	1.34	5.79	75.65
	S2	$\gamma = 3.114 + 2.168 \cdot \left(1 - \exp \frac{-t}{66.543}\right) + \frac{t}{1282.330}$	0.944	1.31	6.18	77.93
	S3	$\gamma = 3.135 + 2.377 \cdot \left(1 - \exp \frac{-t}{95.825}\right) + \frac{t}{1079.789}$	0.972	0.30	6.62	81.45

S1-almost ripe, S2- ripe, S3- overripe, W- area under the creep curves.

The instantaneous elastic strain varied between 1.057 mm and 3.135 mm, the highest values of this parameter being recorded by *Magic* variety; for *Vibrant* and *Elsanta* varieties it can be observed that this parameter presents smaller and close values which imply that these two varieties have a high resistance to mechanical impact. In addition the *Elsanta* strawberries had the highest values of retarded elastic strain (2.473-3.113 mm) predicted by the Burger model, followed by *Magic* variety (2.052-2.377 mm), while the *Vibrant* strawberries had the lowest values of retarded elastic strain (0.483-0.738 mm), these being also the most resistant strawberries to mechanical damage which involves a longer compression and not just mechanical impact. Both the instantaneous and the retarded elastic strain increase with the maturation stages, the highest values being recorded by overripe strawberries (S3 stage) and the lowest by almost ripe ones (S1 stage) which means that fruits resistance decreases during ripening process. According to *Chakespari 2010*, [11] the retardation time (λ_{ret}) represents an important factor in fruits storage period and as Burger model predicted the higher retardation time was recorded by the almost ripe strawberries (98.949-140.83 s), the almost ripe *Magic* variety being characterized by an higher storage time. The absolute average deviation -AAD and the coefficient of determination -R² represents a measure of how much the Burger model predicted data deviates from the experimental data.

The ADD values for the Burger model with four Kelvin Voigt elements range between 0.30 and 4.26, whereas the R^2 values range between 0.926 and 0.983. Considering the above mentioned values it seems that Burger model with four Kelvin Voigt elements can be used successfully for the interpretation of strawberries creep curves and to determine the viscoelastic parameters.

Table 3 presents the Pearson correlation of viscoelastic and physicochemical parameters of strawberries. It seems that some viscoelastic parameters are positively correlated with creep strain (S) and area under the curves (W). A significant positive correlation was recorded between the instantaneous elastic strain (ϵ_1) and area under the curves ($p < 0.01$, $r = 0.805^{**}$); another significant positive correlation being between retarded elastic strain (ϵ_2) and the creep strain ($p < 0.01$, $r = 0.827^{**}$). Regarding the chemical composition, moisture content was positively correlated with the soluble substances concentration ($p < 0.05$), the values of this two parameters increasing during the ripening process. The retarded elastic strain and viscous strain are positively influenced one by the other ($p < 0.05$).

Table 3
Pearson correlation of viscoelastic and physicochemical parameters of strawberries

	S	W	ϵ_1	ϵ_2	ϵ_3	λ_{ret}	M	B	pH	TA
S	1	0.989 ^{**}	0.740 [*]	0.827 ^{**}	0.792 [*]	0.391	-0.027	0.326	0.302	-0.439
W		1	0.805 ^{**}	0.765 [*]	0.721 [*]	0.332	-0.027	0.345	0.394	-0.504
ϵ_1			1	0.244	0.356	0.244	-0.281	0.031	0.575	-0.529
ϵ_2				1	0.779 [*]	0.374	0.188	0.457	-0.023	-0.208
ϵ_3					1	0.160	0.210	0.385	0.129	-0.333
λ_{ret}						1	-0.529	-0.322	-0.397	0.370
M							1	0.794 [*]	0.230	-0.355
B								1	0.473	-0.657
pH									1	-0.949 ^{**}
TA										1

S – strain, W – area under the creep curves, ϵ_1 – instantaneous elastic strain, ϵ_2 – retarded elastic strain, ϵ_3 – viscous strain, λ_{ret} – retardation time; M – moisture, B – Brix concentration, TA – total acidity.

Principal component analysis (PCA)

Principal Component Analysis (PCA) carried out on strawberry samples explains all the data variation; first component (PC1) explains 81% while second one (PC2) explains 19% of the variance in the obtain data. The results of correlations loadings and scores of PCA are presented in Figure 3 and Figure 4 based on this statistical analysis the strawberry samples are distributed in different quadrants. From PCA score, Figure 3, we can observe that PC1 separates the almost ripe strawberry samples (S1) from the other samples (S2 and S3), while the PC2 separates the samples based on strawberry variety.

In Figure 4 – PCA loadings, the parameters distributed in the center of the ellipse (the instantaneous elastic strain and the viscous strain) have an insignificant influence in samples differentiation, while the parameters from outside ellipse (the creep curve characteristic, retardation time, retarded elastic strain, moisture, pH, Brix concentration and total acidity) present a strong influence in samples differentiation.

Figure 3. PCA scores of strawberry samples:
M – Magic, E – Elsanta, V – Vibrant, S1 – almost ripe, S2 – ripe, S3 – overripe.

Figure 4. PCA loadings of strawberry samples parameters:
S – strain, W – area under the creep curves, ϵ_1 – instantaneous elastic strain,
 ϵ_2 – retarded elastic strain, ϵ_3 – viscous strain, λ_{ret} – the retardation time;
M – moisture, B – Brix concentration, TA – total acidity.

The Burger model retardation time is strongly correlated with first component (PC1) and consequently with almost ripe strawberry samples, which showed the lowest values of Brix concentration and the highest total acidity and retardation time. The creep strain (S) influences the *Magic* strawberry projection, this variety being characterized by high values of Burger instantaneous elastic strain.

Conclusions

The compression creep test conducted in this study highlighted that all strawberries samples presents viscoelastic properties influenced by the variety and by the maturity stages. The strawberries from *Vibrant* variety have the highest resistance to mechanical impact and also a high mechanical resistance to compression due to the fact that showed the lowest values of instantaneous and retarded elastic strain. Keeping into account the R^2 and ADD values, the mechanical Burger model with four Kelvin Voigt elements can be successful used to determine the viscoelastic properties of strawberries samples such as instantaneous elastic strain, retarded elastic strain or retardation time. The PCA statistical analysis revealed that creep curves characteristic and Burger viscoelastic properties have a great impact in strawberry samples projection based on variety and maturity stages.

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