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MULTIPLE LINEAR REGRESSION MODEL OF GOLDEN APPLE'S FAILURE CHARACTERISTICS UNDER REPEATED COMPRESSIVE LOAD

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ABSTRACT

In this paper, the multiple linear regression model of mechanical properties related to the failure mechanism of apple tissue under repeated compressive load was investigated. More refined failure characteristics may lead to improved processing and logistics aspects of the given fruits. For our study, the following failure-related factors are considered during the cyclic measurements of Golden Delicious apples: the viscoelastic parameters, the dissipated energy, and the rupture point of the cell-structure, which is described with the time to failure parameter (TTF). For the determination of viscoelastic components, the three element Poynting-Thomson body was applied, and a closed-loop control system is identified with the measured creep data. From the hysteresis loop – in each cycle of the force-deformation parametric curve – the dissipated energy can be calculated with a numeric integration method. The rupture point of the fruit tissue – where the measuring pin is breaking through the peel and the cortex – is observed with a high-framerate video analysis, so that the time index of the failure point can be evaluated. The focus is to define the influence of the mentioned factors to the TTF parameter of the examined fruit material. During the statistical evaluation of the resulted data, the failure of time can be successfully determined with a multiple lienar regression model of the determined viscoelastic and dissipated energy variables. With the resulted equation, the failure time of Golden Delicious apples can be predicted based on the measured failure-related parameters obtained during the compressive load tests.

Keywords: repeated load; fruit damage; analysis of variance; time to failure; mechanical fatigue

INTRODUCTION

Studying the damage resistance and failure susceptibility of fruits are one of the most important topics in the area of food processing and logistics. A very significant amount of the agricultural and horticultural crops never gets to the costumer, because the mechanical effects are often leading to a failure in the cell structure and consequential spoiling of the product, decreasing market value. Failure characteristics of fruit materials can be described with many different approaches. During destructive compressive tests, the stress-deformation curves of biological materials have been investigated from several aspects.

Fruits and vegetables are usually described with viscoelastic models **(Mohsenin, 1986)**, where the creeping and stress relaxation phenomenon have an important role; as **Sitkei (1986)** pointed, the creeping behaviour occurs in more technological and manipulating process (e.g. the settling of silage and granular piles, or the deformation of fruits by their dead weight), but the relaxation time is also an important factor in the area of food industry, e.g. in the case of juice industry **(Gorji Chakespari et al., 2010)**. The fruit firmness is also determined with certain parts of the relaxation curve **(Blahovec, 1996)**. The destructive fruit and vegetable researches are based on the evaluation of the force-deformation characteristics, that resulted during creep or stress relaxation tests **(Tscheuschner and Doan, 1988; Zhao et al., 2017; Miraei Ashtiani et al., 2019)**. These examinations are usually performed with different universal or custom loading devices.

Since most of the postharvest operations are affecting the crops with impact or repeated compressive mechanical forces, the laboratory tests aim to reproduce these circumstances, and observe the fruit material during its colliding or its fatigue process. Fruit-to-fruit damage or collusion with rigid materials can be examined with a pendulum impacting device **(Ferreira et al., 2008; Wang et al., 2018)**, or firmness measurements can be performed with drop tests **(Wang et al., 2009; Vursavus, Kesilmis and Oztekin, 2017)**. In other cases, the dropping of pear fruits **(Yousefi, Farsi and Kheiralipour, 2016)**, the mechanical interaction between two apples **(Ahmadi, Barikloo and Kashfi, 2016)**, or the collusion against a rigid flat plate is simulated with finite element analysis **(Dintwa et al., 2008)**.

For the reproduction of the repeated mechanical effects from various manipulations, some research already experimented with cyclic load: **McLaughlin and Pitt (1984)** investigated a cell-rupture model during their fatigue examinations, while **Lee, Tan and Waluyo (2012)** and **Bohdziewicz and Czachor, (2016)** studied the dissipated energy during cyclic load conditions.

Mohsenin (1986) and **Sitkei (1986)** specified two typical point in the deformation characteristics of the biological materials, which are related to the mechanical failure: the biological yield, and the rupture point. The biological yield point is an initial fracture inside the microstructure of the cell system, which can lead to a more extent damaged volume, and ultimately, to spoiling. However, the biological systems are capable to regenerate, it can be a reasonable limit for the mechanical effects to stay under this value. The rupture point means a significant damage in the biostructure, which indicates the mechanical failure. It often comes with a clearly visible breaking point at the deformation graph, but in some cases – when the loading force is fast – the determination of this time instant can be more difficult.

The applied and absorbed mechanical energy is greatly responsible for the volume of the resulting fruit damage during an impact, a compression, or a vibration process **(Hussein, Fawole and Opara, 2018).** The dissipated energy is strongly related to the failure mechanism of the biological materials, which can be calculated from the hysteresis loop of the stress-strain characteristics; for the investigation of the energy indicators, the area between the loading and unloading curve is usually observed **(Ciupak and Gładyszewska, 2011; Lee, Tan and Waluyo, 2012; Diels et al., 2016)**. In case of certain apple types, the hysteresis parameters are showing a significant relationship with viscoelastic properties **(Lee, Tan and Waluyo, 2016)**. The momentum-formula is also applied for the determination of energy-balance, when the fruits are exposed to colliding during different drop tests **(Lien and Ting, 2014; Stropek and Gołacki, 2013)**.

The energy dissipation related to fatigue degradation and cracking is an active research area in other fields as well; although, the dissipated energy under the hysteresis loop can be determined in each cycles of a repeated mechanical load, it is often questioned, that it is fully or partially reversible, and whether can be linked to the damage or not **(Kim, Roque and Birgisson, 2006; Kahirdeh and Khonsari, 2015)**.

From the aspect of fruit bin and package design, the effect of transportation to the fruit piles is usually inspected during simulated examinations with vibration-pads. The most dangerous frequencies – that causing the highest volume of fruit damage – are determined with accelerometer sensors. According to the consilient report of different studies, the frequency range under 10 Hz is the most dominant, and it is responsible for the most extensive losses **(Fischer et al., 1992; Hinsch et al., 1993; Vursavuş and Özgüven, 2004)**. In order to keep the quality of piles as good as possible – besides the bin and package optimizing – an appropriate transport-planning can be a viable solution as well, if the poorly maintained road segments can be avoided **(Springael, Paternoster and Braet, 2018)**.

In the case of biological or other viscoelastic materials, the creeping curve is divided into different phases, where the last section is beginning with a crack initiation point, which is indicating the failure of the material. However, the literature is not specifying the precise determination of this occurrence, the accurate identification can be very important. Since the stress-strain characteristics of fruits are not always indicating the rupture point clearly and accurately (especially in the case of fast loading speeds, which cause a steep rising in the deformation curve), a image-processing based observation with high framerate can be set for the determination of the failure time – when the measuring pin is getting through the damaged fruit peel and cortex during cyclic compressive testing. Obtaining this parameter, our study aims to explore the influence of the dissipated energy and the viscoelastic parameters to the fatigue mechanism of the selected Golden Delicious apple texture.

Scientific hypothesis

Hypothesis H1: The time to failure (TTF) parameter of pome fruits can be described with the multivariate linear regression of viscoelastic properties and an indicator of dissipated energy.

Hypothesis H2: Our previous study reported **(Farkas, Fenyvesi, and Petróczki, 2019b)**, that the elastic modulus parameters from the viscoelastic model are not showing any dependence of the frequency in case of Golden Delicious apples. The viscous part relates to the applied frequency settings in a non-linear way, so we assume, that the frequency variables will not have any role on the determination of the failure time either.

MATERIAL AND METHODOLOGY

To perform the cyclic load measurements, the custom developed DyMaTest device is applied **(Fenyvesi, 2007; Petróczki and Fenyvesi, 2014)**. The examined apple is placed into a sand bed, where a measuring pin of 4 mm diameter is loading the peel surface in a 10 mm deformation range. The fruits were measured and modelled as a structure of peel and cortex.

Before the investigations, the creeping response of the prepared sand is tested with control measurements. In order to perform this inspection, a solid ball bearing of 32 mm diameter is loaded. The deformation graph is not showing any creeping behaviour in the measuring range of the photoelectric sensor. The sand is dried and filtered with a mesh layer-by-layer **(Pillinger et al., 2018)**, then it is compacted with a metal tamper.

For the current examinations, a cosinusoidal force-function was adjusted in the software environment of the computer-controlled instrument:

$$F_m(t)=F_{max}(1-\cos(\omega t)), \qquad (1)$$

where F_m is the measured cosinusoidal load function, F_{max} is the amplitude of the force (N), and ω is the angular velocity of the loading (s^{-1}).The deformation response is also cosinusoidal, and with the consideration of the creeping process, it is described with the following equation before the rupture point:

$$w_m(t)=jt+k+w_{max}(1-\cos(\omega t-\delta)), \qquad (2)$$

where w_m is the measured deformation function, w_{max} is the amplitude of the deformation (mm), j and k are the coefficients of the linear part of creeping (j denotes the slope and k is the y-intercept), ω is the angular velocity (s^{-1}), while δ is the phase angle difference between force and deformation.

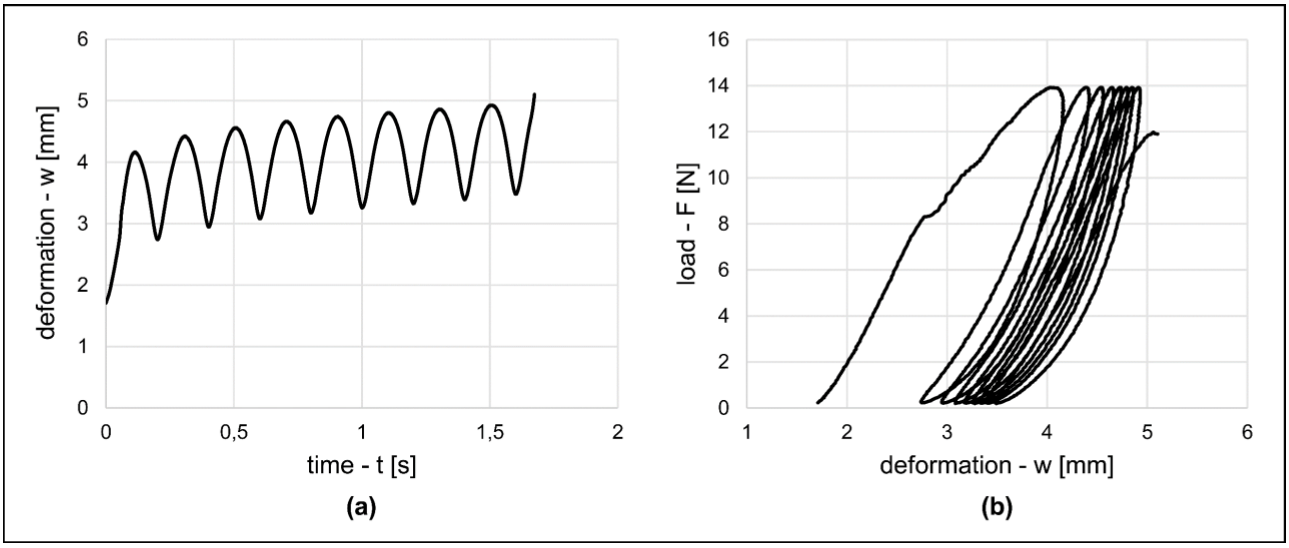

Figure 1 Typical deformation-time (a) and force-deformation (b) characteristics of Golden Delicious apple tissue.

Because of the repeated compressive examinations, the tested biomaterial is showing a dynamic creeping behaviour: while the mean value of the cosinusoidal load is constant, the curves - that envelope the maximum and minimum points of the deformation – have a similar character to the creeping during a constant load. This dynamic creeping can be seen at Figure 1 (a), where the graph of deformation as a dependent of time is presented.

The resulted deformation curves are investigated before the rupture point, where the irreversible failure of the fruit texture is certainly occurring. Because of the relatively fast rising nature of the loading curve, the breaking point is not always showing itself, so this specific occasion is determined with a camera, which is capable of a recording with 240 frames per second. The rupture moment - when the measuring pin is getting through the peel – is registered during the frame analysis (shown in Figure 2) as a time parameter and referred as 'time to failure' in the present study (TTF - **Gnedenko et al., 1999**).

Figure 1 (b) is illustrating the force-deformation characteristic of the examined apples, where the areas between the loading and unloading curves are representing the dissipated energy of each cycle. The calculation of this internal loop area is based on the following general formula:

Figure 2 Frame from the video analysis during the registration of the time to failure (TTF) parameter.

$$E_D = \int_0^T F_m \frac{dw}{dt} dt, \qquad (3)$$

where E_D denotes the dissipated energy (N.mm), while T is the time period of the given load cycle (s). For theoretical calculation, inserting equation (1) and (2) into our previous formula:

$$E_D = \int_0^T F_{max}(1 - \cos(\omega t))(j + \omega w_{max} \sin(\omega t - \delta))dt. \qquad (4)$$

For the numeric integration of equation (4), the resulted load and deformation data from the cyclic compressive test are available as lookup-table inputs in a Simulink block diagram. During the evaluation of the measurements, the ratio of dissipated energy **(Delgadillo and Bahia, 2005)** is calculated:

$$E_{DR} = \frac{\sum_{i=0}^{n} E_{Di}}{E_{Dn}}, \qquad (5)$$

where E_{DR} is the ratio of dissipated energy (-), $\sum_{i=0}^{n} E_{Di}$ denotes the sum of dissipated energy at the given load cycle (N.mm), and E_{Dn} is the dissipated energy of the last calculated cycle (N.mm).

The peak value of this ratio is used to mark the inner rupture of the fruit material (Figure 3): since this maximum value is clearly connected to the failure mechanism of the crops **(Farkas, Fenyvesi and Petróczki, 2019a)**, it must be included during the correlation analysis.

The viscoelastic behaviour of the examined Golden Delicious apples is investigated with a Simulink-based control loop system. For the identification, the presented measurement data before the rupture point of the fruit material is applied. The measured deformation (wm) and the calculated (w) output of the mathematical model are displayed and compared in one scope (Figure 4).

The Poynting-Thomson body contains two elastic components (E1, E2 – N.mm$_{-1}$), and one viscous part (η – Ns.mm$_{-2}$). The three-element visoelastic structures are the simplest models, that can handle the creep phenomenon of the given material – where the constant stress is causing an

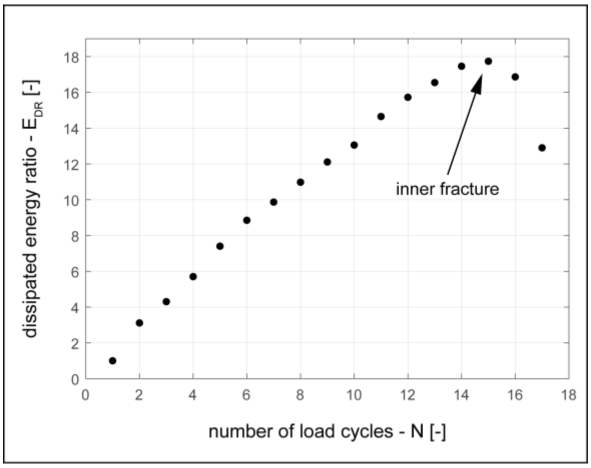

Figure 3 Energy peak related to inner fracture during the fatigue process of Golden apples **(Farkas, Fenyvesi and Petróczki 2019a)**.

increasing trend in the deformation process. With the control loop system and a minimum search method, the three viscoelastic parameters can be determined with the best fit of the calculated deformation to the actual deformation curve **(Farkas, Fenyvesi and Petróczki, 2019b)**.

For our study, Golden Delicious apples were chosen for the experiments, which is representative at the Hungarian food producing and the consumer market.

The measurements were performed on 25 Golden Delicious specimens. Each fruit was loaded in 6 different spots, using different frequency settings, so the described viscoelastic parameters and dissipated energy values were evaluated in 150 cases overall.

The samples were stored in an ambient laboratory environment (~25 °C, with the relative humidity of ~60 RH%). The fruit sample parameters were: ~160 g (±30 g), density: ~0.875 g.cm^{-3} (±0.03 g.cm^{-3}). The measurements were performed within the confines of few hours, so degradation and further ripening could be neglected during the investigations.

According to the literature, the most dangerous frequency values were reported under 10 Hz during the transportation process **(Fischer et al., 1992; Hinsch et al, 1993; Vursavuş and Özgüven, 2004)**, so the frequency values were adjusted in this range: the steps were divided for nearly identical intervals (2.5, 3.7, 5, 7.5, 10, and 11.6 Hz, respectively) set by practical options on the measuring device.

Statistic analysis

For the statistical analysis of the measurement data, we used the SPSS statisctics 25 software, where the linear regression tool is applied. To describe the failure time as a function of the measured dissipated energy parameters and the components of the Poynting-Thomson model, multiple linear regression models were examined. For the verification of these models, we used the analysis of variance (ANOVA) method.

RESULTS AND DISCUSSION

Besides the resulted parameters from the compressive load tests, the applied frequency vales are also considered during our investigations.

From the viscoelastic properties, the viscous part is clearly the most important parameter in the characterization of the failure mechanism. Our previous study showed, that only these values are standing in strong correlation with the frequency settings, but this trend has a non-linear nature **(Farkas, Fenyvesi and Petróczki, 2019b)**. From the aspect of linear description of failure time, the frequency parameters did not appear in any model suggestions (presented in Table 1).

The relationship between the E_{DRmax} values and the TTF parameter is representing the connection of the inner damage of cell structure and the rupture point. This relation could add another important aspect to the model to improve the approximation of the failure behavior in case of pome fruits.

From these variables, there are four regression model is resulted with different coefficients of determination (shown in Table 1). The elastic response of the fruit tissue must determine the failure process as well: in model 3, E_1 modulus is improving the fit considerably, so this elastic parameter is reasonable to include into the characterization. However, E_2 is also increasing the R^2 in model no. 4, the difference between the two options is so small, that this variable just means an unnecessary to describe the elastic behavior – the E_1 is representing it for the given material

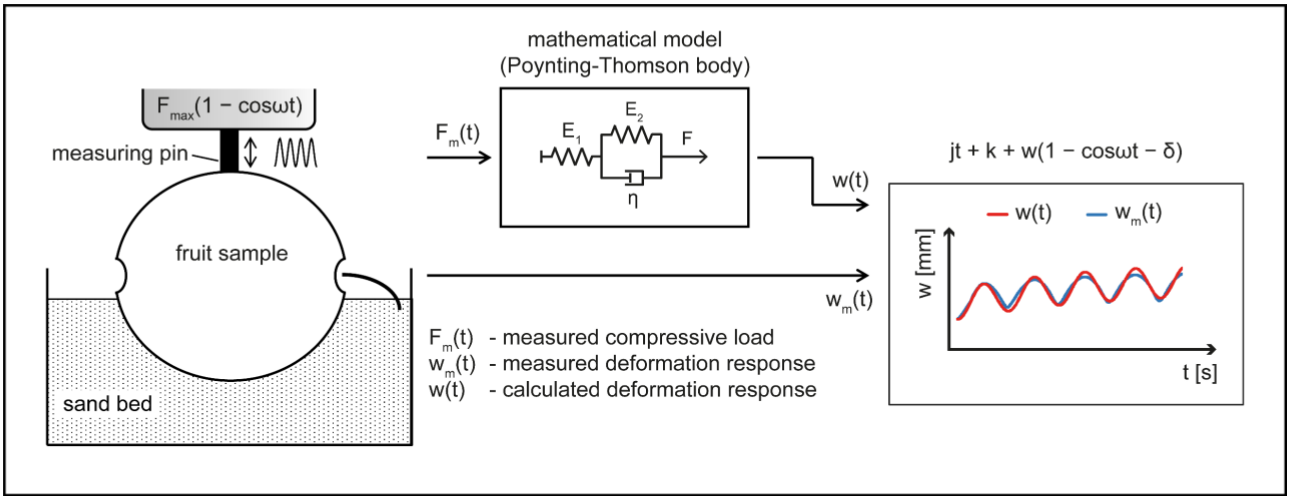

Figure 4 Identification of the Poynting-Thomson viscoelastic model **(Farkas, Fenyvesi and Petróczki, 2019b)**.

already. Considering these standpoints, model no. 3 is chosen with the following coefficients:

$$TTF = 0.533 + 2.736\eta + 0.141E_{DRmax} - 0.261E_1 \quad (6)$$

We verified the validity of our model with the analysis of variance: the significance level is $p < 0.05$, so the resulted model is applicable for the quantitative description of the investigated phenomena (shown in Table 2).

Figure 5 (a) is showing the relationship between the measured time to failure parameters and the predicted values from the applied regression model, while (b) is representing the categories of relative difference, where all the 25 specimens were divided. Most of the examined samples fall into the 5 – 10% range of error, the average of difference is 6.20% in the case of 13 apples. This group is followed by the category of error under 5%, where the average value is 2.61%, the data were obtained from 6 samples. 5 of the investigated apples are showing 12.81% relative difference, and 1 sample resulted 20.22% during the comparison of the dependent variable. This consequence about the relative error is composed of three different aspects:

1. The coefficients of the Poynting-Thomson model were also determined with a regression method during the parameter identification **(Farkas, Fenyvesi and Petróczki, 2019b)**. Although the R_2 values were fell into the 0.967 – 0.998 range when the measured creep data was compared with the Simulink-based visoelastic model, the relatitve error of this approximation cannot be calculated.
2. The registration of the time to failure parameter was performed in a dynamically changing section during the rupture process: the frame analysis also carrying the possibility of error, since the sample rate has its own limitations.
3. The dissipated energy calculations were pointing to the calculation of the E_{DRmax} value, which is indicating the inner rupture of some level, but the accurate background of this

Table 1 Linear regression model summary.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.902(a)	.814	.812	1.03413	.814	641.502	1	147	.000
2	.963(b)	.927	.926	.64922	.113	226.984	1	146	.000
3	.971(c)	.943	.941	.57824	.015	39.039	1	145	.000
4	.972(d)	.945	.943	.56840	.002	6.064	1	144	.015

Note: a Predictors: (Constant), η; b Predictors: (Constant), η, EDRmax; c Predictors: (Constant), η, E_{DRmax}, E_1; d Predictors: (Constant), η, E_{DRmax}, E_1, E_2.

Table 2 ANOVA summary of the linear regression model.

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	794.762	3	264.921	792.307	0.000
Residual	48.483	145	0.334		
Total	843.245	148			

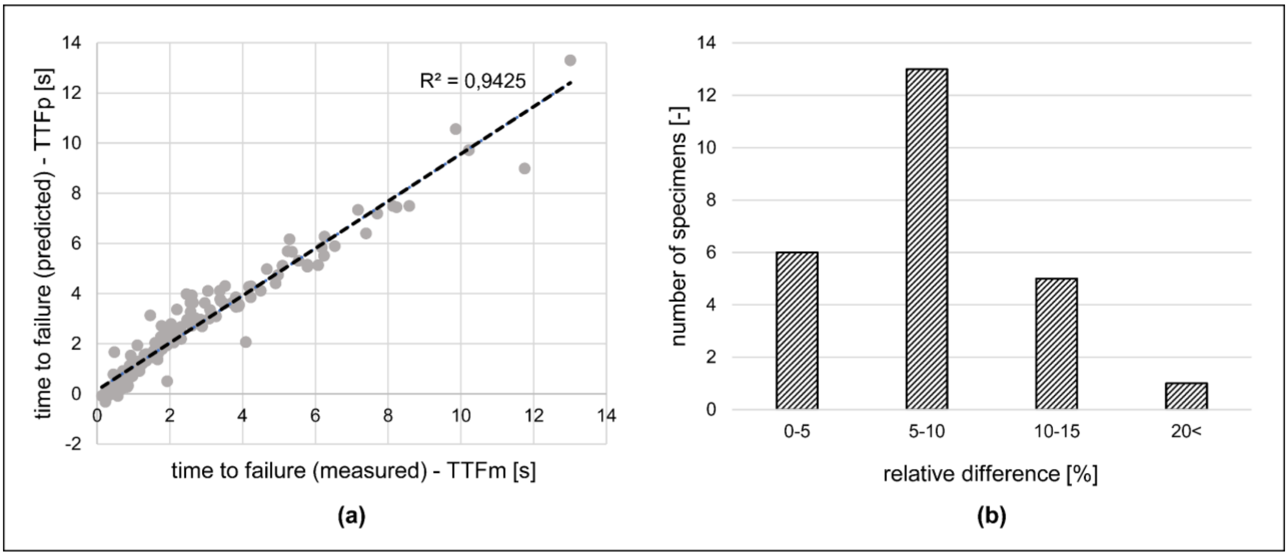

Figure 5 Relationship betweeen the measured and calculated TTF parameter in case of 150 tests (a). Number of specimens in different relative error categories in case of 25 examined apples (b).

relationship is still waiting for more investigations. While the circumstances of the cracking propagation e.g. in the area of asphalt pavement is more explored **(Sangpetngam, 2003)**, the role of the dissipated energy ratio in the cellular level is a future plan to investigate in case of different fruit materials.

In the case of our study, the following answers were formed for our hypotheses:

1. A multiple linear regression model with certain visoelastic parameters and a dissipated energy indicator can describe the failure time of Golden Delicious apples with an overall relative difference of 7.22%
2. The frequency settings in the range of 2.5 – 11.6 Hz are not influencing the failure time in the resulted linear regression model.

The resulted equation is a simple linear description of the Golden apples' failure mechanism, which can be applied for further transportation studies or cyclic load simulations.

CONCLUSION

Viscoelastic modelling and dissipated energy calculations are commonly applied methods in the studies about damage susceptibility of different fruits: the parameters from these approaches can be related to the failure mechanism separatel. In our research, we have extended on the previous approaches to supply variables for a multiple regression model at the same time.

The visoelastic coefficients were determined with a custom developed control-loop method, while the dissipated energy calculation was successfully implemented from another research area to the present investigations of fruit materials.

The novel frame-by-frame image analysis allows to gather direct information from a rapidly changing process, supplementing the mathematical approach for registering the rupture phenomenon. Based on the measurement results from the developed methods, our novel, multiple linear regression model can describe the time to failure occasion in case of the examined Golden Delicious apples in the most important frequency range. Also, the presented model can describe the failure characteristics with an acceptable relative difference. It is suggested, that the model can be used for further fruit types. The paper presents a simple three-element material description, but the failure mechanism can be characterized in further experiments, where the visoelastic approximation can be extended with more complex variables.

The current focus of the compressive load settings (which is aimed to reproduce the most dangerous frequencies during the transportation) can also be extended with other load circumstances from other manipulating stages of the food processing chain.

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