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# MECHANICAL PROPERTIES OF BUCKWHEAT PERGA

# MEHANIČKE OSOBINE HELJDINE PERGE

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## *ABSTRACT*

*Owing to a limited body of information on perga properties in the literature, the compressive properties of perga were determined in this study using uniaxial compressive tests. Certain mechanical properties such as the failure stress and strain and the modulus of elasticity can be used to evaluate the mechanical behavior of buckwheat (Fagopyrum esculentum) perga pellets under static loading. The Andilog Stentor 1000 testing machine (Andilog Technologies, Vitrolles, France) was employed for the uniaxial compression testing conducted. The perga samples considered were tested at different strain rates and loading speeds: four speeds ranging from 10 to 90 mm/min were used to achieve different strain rates. The influence of strain rates on the sample stress state was studied. The nonlinear regression model was tested to account for the stress-strain curves obtained. The loading curves of dependence of the stress on the strain were formed. Different strain rates and loading speeds were found to exert a significant effect on the stress and strain state of the perga samples examined, i.e. their overall firmness.*

***Key words:*** *firmness, mechanical properties, perga, strain rate.*

## *REZIME*

*Podaci o mehaničkim osobinama perge (pčelinji proizvod – fermentisani polen) veoma su retki. Za ispitivanje mehaničkih osobina primenjen je jednoosni test kompresije uzoraka perge. Mehaničke osobine, kao što su zavisnost deformacije od rastućeg napona, kao i modul elastičnosti mogu se koristiti za procenu ponašanja peleta heljdine perge (Fagopirum esculentum) pri statičkom opterećenju. Za testove jednoksijalne kompresije korišćen je uređaj Andilog Stentor 1000 (Andilog Technologies, Vitrolles, Francuska). Uzorci perge testirani su različitim veličinama deformacije, a ponašanje pri konstantnoj brzini upoređeno je sa ponašanjem pri različitim brzinama deformisanja. Eksperimenti su izvedeni pri četiri brzine deformisanja od 10 do 90 mm/min da bi se postigli različite veličine deformacije. Istraživan je uticaj veličine deformacije na napon. Ispitan je nelinearni regresioni model koji može objasniti krive zavisnosti napona i veličine deformacije. Dobijene su krive zavisnosti napona od deformacije. Uticaj veličine deforamcije i brzine deformisanja na napone i deformaciju uzoraka pri maksimalnom naponu na krivoj napon-deformacija, odnosno na čvrstoću uzoraka perge.*

***Ključne reči:*** *čvrstoća, mehaničke osobine, perga, veličina deformacije.*

## INTRODUCTION

Owing to its high nutritive value, perga is bee pollen used both as the primary food source for the hive and as food for humans. However, there is a limited body of information on the mechanical properties of perga, whereas the mechanical properties of perga hexagonal prisms are practically unknown.

The chemical and biochemical composition of bee pollen depends mostly on the botanical origin, harvest time, soil and climatic conditions (*Bleha et al., 2015).* The term "bee bread" refers to the original bee pollen stored in honeycombs. Prior to storage, bee bread (or perga) is processed by bees and ultimately fermented by the addition of various bee enzymes and honey. This type of lactic acid fermentation is similar to that in yoghurts (and other fermented milk products) and renders the end product more digestible and enriched with new nutrients *(Brindza et al., 2015).* Bee bread is a product of the hive obtained from pollen collected by bees, to which they add honey and digestive enzymes prior to storing it in the combs. The lactic fermentation which consequently ensues enhances the conservation level of stored bee bread *(Zuluaga et al., 2015).* The process of bee bread formation starts with pollen gathering, which is then mixed with flower nectar or honey and saliva by bees and carried to the beehive (where non-flying bees fill honeycomb cells with this mixture up to three quarters of the cell volume).

The mechanical properties of biomaterials have been studied by a number of authors. *Babić et al. (2013)* conducted stress-strain uniaxial compression tests to examine the response of biomaterials to an externally applied force that deforms the body of the material, thus causing changes in the material dimension, shape or volume. These tests provided important information about the elastic and plastic behaviour of the materials considered. *Babić et al. (2012)* described the stress-strain diagrams of the biomaterials tested, which are graphical representations of the simultaneous values of force and displacement recorded during testing. They also determined the bioyield point force of certain biomaterials such as sunflower fruits.

The rheological properties of biomaterials greatly affect their mechanical properties. *Božiková and Hlaváč (2013)* examined the dependence of material resistance against the probe rotation, which was used during rheological property measurements. They studied the dynamic viscosity-temperature dependence of two bio-oil types (namely Plahyd N and Plahyd S) and recorded exponentially decresing trends.

*Hlaváčová et al. (2018)* argue that rheological data are important for product quality evaluation, engineering calculations and process design. It is necessary to know and understand the behaviour of different materials to determine the size and energy requirements of associated equipment and production processes. Rheological models built upon experimental measurements can also be useful in the design of material engineering processes relative to energy and mass balances.

The purpose of this paper is to examine the behaviour of perga hexagonal prism pellets under compressive loading. The failure strength and strain, the elastic modulus and the influence of strain rates and loading speeds on the stress state of buckwheat perga were determined and correlated in the present study.

## MATERIAL AND METHOD

Buckwheat *(Fagopyrum esculentum)* perga pellets of hexagonal shape were used for the measurements conducted. The buckwheat perga samples were collected in the selected regions of Ukraine (Poltava and Dnepropetrovsk) and taken from their honeycombs. All the perga samples were monofloral. They were stored permanently at a temperature of 4 °C – 6 °C and an air humidity of (40 – 60) % in the refrigerator. The moisture of the perga samples was 14 %. The average length of the perga samples was 11.508 ± 0.162 mm with an average pellet hexagon side of 2.952 ± 0.018 mm.

Static compressive loading in the uniaxial direction was used for the perga sample testing with the Andilog Stentor 1000 testing machine (Andilog Technologies, Vitrolles, France). The compression of the perga pellet samples considered was performed using two parallel plates (Fig. 1).

*Fig. 1. Compression test of the cylinder perga hexagonal prism pellets samples using parallel plates – uniaxial loading*

The experiments were conducted at different loading speeds: 10, 30, 60 and 90 mm/min. The force $F$ (N) and the deformation $D$ (m) were measured using the acquisition software RSIC ver. 4.06. The stress and strain values were calculated for the hexagonal samples under compressive loading. The loading curves of dependence of the stress on the strain were formed. The Cauchy's strain $\varepsilon_c$ gives the relative deformation relative to the initial sample height $l_0$:

$$\varepsilon_c = \frac{\Delta l}{l_0} \tag{1}$$

The ultimate stress $\sigma_u$ is given as the force $F$ divided by the original cross section $A_0$ of the sample:

$$\sigma_u = \frac{F}{A_0} \tag{2}$$

The cross sections $A_0$ of the hexagonal shape were calculated using the following equation:

$$A_0 = \frac{3}{2}a^2\sqrt{3} \tag{3}$$

where $a$ is the side of the hexagon m.

The strain rate $\frac{d\varepsilon}{dt}$ is defined as the change of the relative deformation per time:

$$\frac{d\varepsilon}{dt} = \frac{d}{dt}\left(\frac{\Delta l}{l_0}\right) = \frac{d}{dt}\left(\frac{l-l_0}{l_0}\right) = \frac{1}{l_0}\frac{dl}{dt} = \frac{v}{l_0} \tag{4}$$

where $\varepsilon$ – relative deformation, $\Delta l$ – contraction, $l_0$ – initial length, $l$ – length after contraction, $v$ – speed, $t$ – time, $\frac{d}{dt}$ – time derivation.

The method based on the elastic theory and the Hook's law was used to determine the moduli of elasticity. The moduli of elasticity were calculated as the slope of the linear part of the stress – strain curves using the regression method. The failure strength and strain were determined from the maximum values of the material strain, whereas the stress was determined from the maximum values of the loading curves. The effects of strain rates and loading speeds on the buckwheat perga stress state were studied.

## RESULTS AND DISCUSSION

The geometrical parameters and bulk density of the perga buckwheat pellet samples considered are shown in Table 1. The following average values of the pellet samples were computed: $m$ = 0.284 ± 0.005 g, $l$ = 11.508 ± 0.162 mm, the pellet hexagon side $a$ = 2.952 ± 0.018 mm, the pellet cross section $A_0$ = 22.652 ± 0.276 mm$^2$, the pellet volume $V$ = 260.82 1± 5.129 mm$^3$ and of the pellet bulk density $\rho$ = 1.092 ± 0.021 kg.m$^{-3}$.

*Table 1. Geometrical parameters of the perga samples considered: a – size of the side of the perga hexagon, $A_0$ – cross section of the sample, l – length of the sample, m – mass of the sample, V – volume of the sample, $\rho$ - bulk density of the sample and SD – standard deviation*

| n | a (mm) | $A_0$ (mm$^2$) | l (mm) | m (g) | V (mm$^3$) | r (kg.m$^{-3}$) |
|---|---|---|---|---|---|---|
| 1 | 3.00 | 23.42 | 11.95 | 0.29 | 279.84 | 1.04 |
| 2 | 3.00 | 23.42 | 11.70 | 0.27 | 273.98 | 0.99 |
| 3 | 2.94 | 22.53 | 11.10 | 0.27 | 250.03 | 1.08 |
| 4 | 2.92 | 22.09 | 11.90 | 0.31 | 262.82 | 1.18 |
| 5 | 2.89 | 21.65 | 11.20 | 0.29 | 242.49 | 1.20 |
| 6 | 2.83 | 20.79 | 9.75 | 0.25 | 202.73 | 1.23 |
| 7 | 3.18 | 26.20 | 11.95 | 0.30 | 313.06 | 0.96 |
| 8 | 2.92 | 22.09 | 12.35 | 0.32 | 272.76 | 1.17 |
| 9 | 2.86 | 21.22 | 12.30 | 0.32 | 261.00 | 1.23 |
| 10 | 2.86 | 21.22 | 11.45 | 0.31 | 242.97 | 1.28 |
| 11 | 3.03 | 23.87 | 12.10 | 0.29 | 288.82 | 1.00 |
| 12 | 2.92 | 22.09 | 10.90 | 0.26 | 240.74 | 1.08 |
| 13 | 2.89 | 21.65 | 12.75 | 0.27 | 276.05 | 0.98 |
| 14 | 2.94 | 22.53 | 11.65 | 0.27 | 262.42 | 1.03 |
| 15 | 2.94 | 22.53 | 12.40 | 0.31 | 279.31 | 1.11 |
| 16 | 3.06 | 24.33 | 11.10 | 0.26 | 270.03 | 0.96 |
| 17 | 2.97 | 22.97 | 11.45 | 0.29 | 263.00 | 1.10 |
| 18 | 2.92 | 22.09 | 10.90 | 0.27 | 240.74 | 1.12 |
| 19 | 3.03 | 23.87 | 10.85 | 0.28 | 258.99 | 1.08 |
| 20 | 2.94 | 22.53 | 10.40 | 0.24 | 234.26 | 1.02 |
| **Average** | **2.952** | **22.652** | **11.508** | **0.284** | **260.801** | **1.092** |
| **SD** | **0.018** | **0.276** | **0.162** | **0.005** | **5.129** | **0.021** |
| **Coeff.of Var. (%)** | **0.602** | **1.219** | **1.411** | **1.786** | **1.966** | **1.925** |

The dependence of the stress on the strain for the five perga samples considered at a loading speed of 10 mm/min is shown in Fig. 2. The compression diagrams of the perga samples at loading speeds of 30, 60 and 90 mm.min$^{-1}$ were also created. The stress – strain curves were characterized by the peaks which represent the firmness limits of the perga pellet samples considered. The values of the strain and stress sample state were determined on the basis of these peaks. The moduli of elasticity

were determined as the slopes of the linear parts of the stress – strain curves (Fig. 3). The regression equations presented in Fig. 3 indicate the values of the moduli of elasticity. The compressive parameters of perga hexagonal pellet samples are shown in Table 2. The following average compressive parameters were computed at a loading speed of 10 mm/min (Table 2): the failure stress = 264.070 ± 30.046 kPa, the failure strain = 0.149 ± 0.013 and the modulus of elasticity = 2033.180 ± 334.670 kPa. The value variations range from 9 % to 17 %.

The average dependence of the stress on the strain, computed from the measured values of the compression diagrams for the perga hexagonal pellets at loading speeds of 10, 30, 60 and 90 mm/min, was also determined (Fig. 4). The stress and strain values were calculated as the mean values of those obtained for the five samples considered at each loading speed. The average values of the failure stress and strain are shown in Fig. 4. The effects of different loading speeds on the sample stress were not confirmed due to the nonuniformity of the perga samples considred.

The average moduli of elasticity were determined as the slopes of the linear parts of the stress – strain curves (Fig. 5). The regression equations presented in Fig. 5 indicate the values of moduli of elasticity recorded.

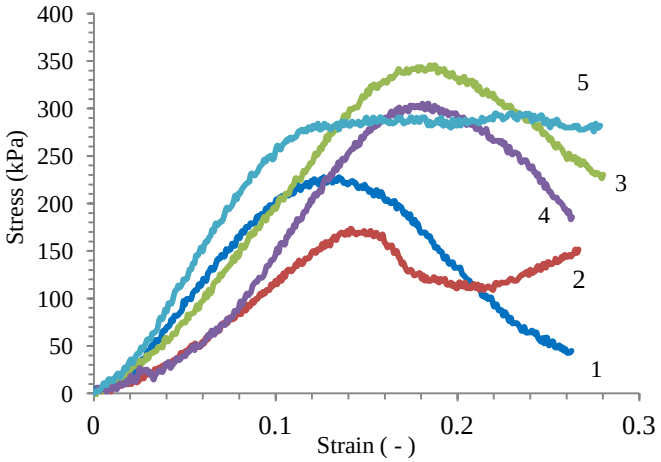


*Fig. 2. Compression diagrams of the five perga hexagonal pellets at a loading speed of 10 mm/min between two parallel plates*

*Table 2. Compressive parameters of the perga hexagonal pellet samples at a loading speed of 10 mm/min (SD – standard deviation, VC – variation coefficient)*

| n | Failure strain ( - ) | Failure Stress (kPa) | Modulus of Elasticity (kPa) |
|---|---|---|---|
| 1 | 0.126 | 227.56 | 2420.80 |
| 2 | 0.143 | 169.19 | 1246.90 |
| 3 | 0.179 | 341.70 | 2169.00 |
| 4 | 0.179 | 302.09 | 1322.40 |
| 5 | 0.118 | 279.81 | 3006.80 |
| **Average** | 0.149 | 264.070 | 2033.180 |
| **SD** | 0.013 | 30.046 | 334.670 |
| **VC (%)** | 8.655 | 11.378 | 16.460 |

The average values of the perga pellets considered (namely their failure strength, failure strain and modulus of elasticity), calculated on the basis of the diagrams in Figures 4 and 5, are shown in Table 3. The failure strain of the samples considered increased with the increased loading speed. However, the failure strain and modulus of elasticity of the samples considered changed irregularly. The effect of strain rates on the sample stress state was shown in Fig. 6. The dependence of the sample stress state on the strain rate was determined at strain rates of 0.10, 0.15, 0.20 and 0.25. The dependence values were parabolic, whereas the relationship between the sample stress state and the strain rate was found to be nonlinear.

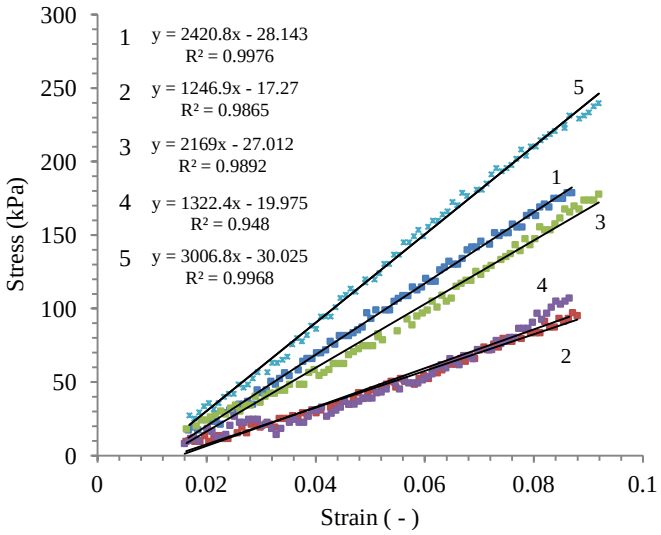


*Fig. 3. Determination of the moduli of elasticity of the five perga hexagonal pellets at a loading speed of 10 mm/min between two parallel plates*

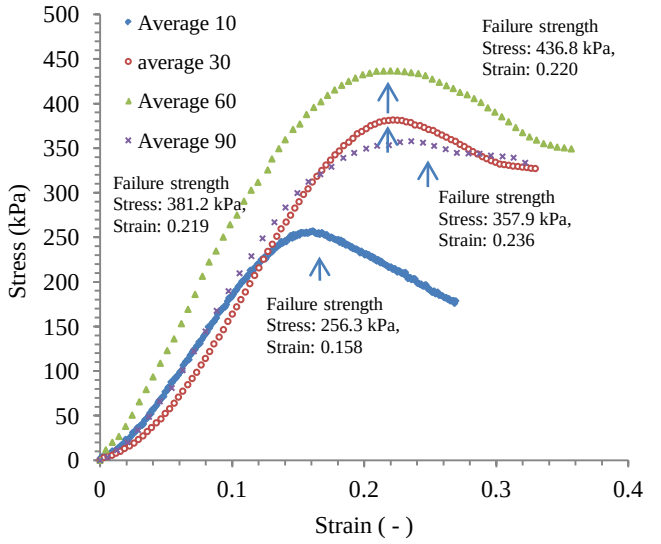


*Fig. 4. Compression diagrams for the average values of the perga hexagonal pellets at loading average speeds from 10 mm/min to 90 mm/min between two parallel plates. The stress and strain values were calculated as the mean values of those obtained for the five samples considered at each loading speed.*

*Table 3. Average compressive parameters of the perga hexagonal pellet samples obtained from Figs. 4 and 5*

| Speed (mm.min$^{-1}$) | Failure strain ( - ) | Failure Stress (kPa) | Modulus of Elasticity (kPa) |
|---|---|---|---|
| 10 | 0.158 | 256.3 | 2043.0 |
| 30 | 0.219 | 381.2 | 1814.2 |
| 60 | 0.222 | 436.8 | 2891.7 |
| 90 | 0.236 | 357.9 | 2324.8 |

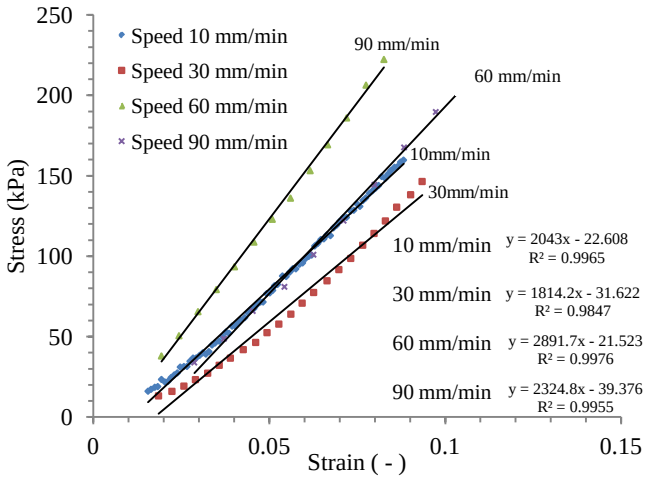


*Fig. 5. Determination of the average moduli of elasticity of the perga hexagonal pellets at loading speeds from 10 mm/min to 90 mm/min between two parallel plates. The lines were calculated as the mean values of those obtained for the five samples considered at each loading speed.*

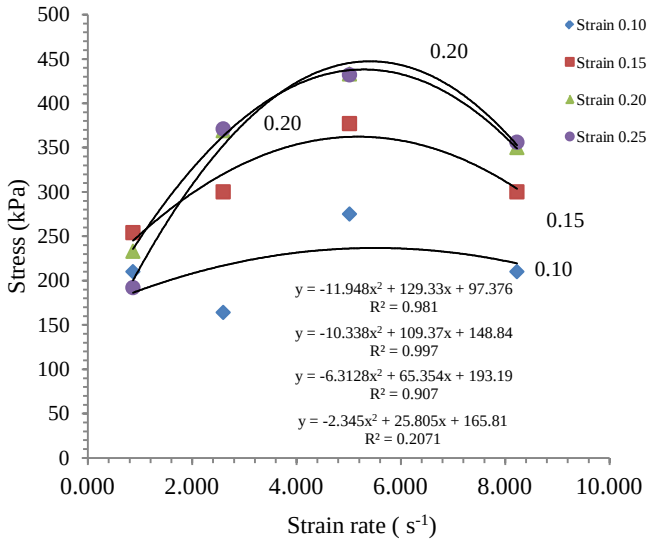


*Fig. 6. Dependence of the sample stress on strain rates for the perga pellets considered at strain rates from 0.1 to 0.25*

## CONCLUSION

The geometric parameters of the perga pellet hexagonal samples were measured and calculated.

The uniaxial compression of the pellet samples considered was performed and the dependence of the sample stress on the strain rate was calculated.

The average values of the perga pellet failure strength, failure strain and modulus of elasticity were obtained.

The sample failure strain increased with the increased loading speed. The sample failure strain and modulus of elasticity changed irregularly.

The effects of the strain rate on the sample stress state were parabolic, whereas the relationship between the strain rate and the sample stress state was found to be nonlinear.

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