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ANISOTROPY OF MECHANICAL PROPERTIES OF MUSHROOMS (*AGARICUS BISPORUS* (J.E. LANGE)IMBACH)

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Abstract. Mechanical and rheological properties of mushrooms in groups selected on account of shape, size and the time of cropping were investigated. Strength tests, hysteresis tests and creep tests of mushrooms compressed between two parallel plates were carried out. Values of the index W_P of the work of deformation inputs, modulus of elasticity E_C and stress σ_{obl} were calculated. Susceptibility to creeping through calculation of the number of days to doubling of the strain value based on MacLeod equation was determined. Anisotropy of mechanical properties was reported, depending on the direction of loading and the size of a mushroom. Modulus of elasticity E_C has a value of 0.5 MPa at the load in the axial direction and 0.3 MPa in the radial direction not depending on the size of a mushroom. Diversity of the value of index Wp from 7 $J \cdot kg^{-1}$ at the load in the axial direction to 3 $J \cdot kg^{-1}$ the radial direction. Increase of pressures admissible for the axial direction may the reason for limiting the time of storage of this raw material to several days.

Key words: strength, hysteresis, creep, mushrooms, anisotropy, plastic flow

The list of symbols:

W_p – index of the work of deformation unit inputs ($J \cdot kg^{-1}$),
E_C – apparent modulus of elasticity (MPa),
σ_{obl} – determined stress (MPa),
ε – deformation of a sample (-),
$F_{(\lambda)}$ – measured instantaneous value of the load (N),
$d\lambda$ – elementary dislocation in the direction of the acting force (m),
ξ – coefficient including the size of the sample (m^{-3}).

Introduction

Mushrooms constitute a low percentage as a source of nutrition for people, however, they are significant in diversification of consumer's diet. In our country, almost 200 thousand tonnes of mushrooms is produced, which ensures the second position among the European producers and the fourth in the world (Sakson, 2008).

Contrary to green plants, mushrooms are characterized with a specific appearance, chemical composition, development and the way of life. Except for nutrients from organic matter, they need appropriate temperature and moisture for life, many factors may influence development of mushrooms (Gapiński, Woźniak 1999).

Although, mycelium seems to be a proper organism, the most important parts from the point of view of producers are reproductive organs, called fructifications. Pulp (trama) of mushrooms is formed from cells called hypae; their chitin walls cover protoplasm. It is a significant difference in comparison to cellulose cell walls in green plants tissues. Mushrooms may differ in shape, surface, size, consistency and colour in specific stages of their development (Szudyga, Maszkiewicz, 1995).

Pileus is the most important part of a mushroom, there is a hymenophore in its bottom part, composed of laminae. Round, half-round or oval pilei have the biggest commercial meaning. A stem during development of a mushrrom raises and supports a pileus. The shape of a pileus in the initial stage of development is clubbed, later cylindrical.

Except for taste values also possibility of transport and storage resulting from the pulp resistance to mechanical loads decide on the quality of mushrooms as a food product (Burton 1989).

Investigating strength properties of the trama of the mushrooms stem is not difficult on account of its cylindrical shape. Cylindrical or cube shaped samples are collected for the research of the pileus trama properties (Gormley, 1969, Noble et al. 1997). Tests of the texture are carried out in the form of a standard shearing test KSC (Gormley, 1969), measurement of the puncture force (Zivanovic et al., 2000), analysis of a profile TPA is carried out (Jaworska i in., 2010). Mc Garry and Burton (1994) based on the penetration test proved that even five time higher diversity of strength against puncture of the trama of the mushrooms stem depending on the place of the load application occurs. It results from changes of the researched material density which occur with time after cropping.

The objective, scope and methodology of research

The objective of the research was to determine by means of an empirical method the values of mechanical and rheological properties of mushrooms. The values of the following physical properties were determined: mass, density and moisture and rheological properties in the form of interim strength, work of deformation and coefficient of elasticity.

Based on the measurement of texture one may conclude on the resistance of mushrooms against direction of the load application. It mainly results from transferring deformations and strains, which come from bending moments, cutting forces and normal forces. They result in local corruption of the structure continuity, cracks and crumbles which are significant for the quality of the products and possibility of its transport or storage (Resolution of the EC Commission, 2004).

A quick test was carried out in the form of the test of compression carried out in two mutually perpendicular directions of the load application, five repeats for each direction for determination of mechanical properties of mushrooms. Since mushrooms were selected on account of the shape, size and the term of cropping, three groups of the research objects were determined. First group consisted of species of 25-35 mm dimensions, in the second group of the same crop, mushrooms dimensions were 35-45 mm. Group 3 was composed of mushrooms of 35-45 mm dimensions, but they came from a later crop. An average value of the force responding to interim resistance was determined for each group. Then, hysteresis tests of deformations and creep tests at the load determined at the level of 40% of the determined force were carried out. During analysis of resistance and rheological tests also a modulus density and moisture of the investigated material were determined.

The research was carried out in the Laboratory of Agrophysics of the Institute of Agricultural Engineering of the Wrocław University of Environmental and Life Sciences. A test machine Instron 5566 with a tensometric head 2525-806 of a scope up to 1kN (precision 0.25%) was applied. Compression tests were carried out in a parallel direction (axial) to the stem of a mushroom and in the perpendicular directions (radial). The speed of deformation during a strength test, in the hysteresis tests and in the initial phase of the creep test was $5 \cdot 10^{-5}$ m·sec^{-1}.

Work of deformation inputs during compression of the research objects was measured. On account of the weight and dimension diversity of mushrooms for comparison of work inputs of deformation in the interim test, the index W_P including the mass of the investigated objects was used:

$$W_p = \frac{W}{m} \quad (\mathrm{J \cdot kg^{-1}}) \tag{1}$$

where:
- W – work of deformation,
- m – mass of a mushroom.

Value of the apparent elasticity modulus E_C, treated as a modulus which determined relation between the calculated value of stress and relative strain ($\sigma_{obl} - \varepsilon$) was accepted as a measure of the material resistance to the compression load (Bohdziewicz, Czachor 2010). For calculation of the value of this modulus a developed method of measuring round objects for calculation of values was applied (Bohdziewicz, 2008). Calculation formula takes in the following form:

$$E_C = \frac{\xi \cdot \int_0^{\lambda} F_{(\lambda)} \cdot \mathrm{d}\lambda}{\varepsilon^2} \tag{2}$$

where:
- $F_{(\lambda)}$ – force,
- ξ – coefficient which includes dimensions of an ellipsoid of the research object,
- ε – relative deformation in the direction of the active load,
- $\mathrm{d}\lambda$ – unit relocation.

Mac Leod (1955) equation was applied for assessment of changes in the object subject to long-lasting loads:

$$\varepsilon_1 = \varepsilon_0 \left(\frac{t}{b} \right)^m \tag{3}$$

where:
t – test duration,
b, m – constants which characterized properties of the material,
ε_0 , ε_1 – deformation property at the start and at the end of the test.

Constant b was calculated based on the equation:

$$b = \sqrt[m]{\frac{\varepsilon_0}{10^x}} \tag{4}$$

At determination of the modulus value m the method of small squares was applied.

Determination of time t theoretical deformation of the sample ε_1 responding to the doubled value ε_0 is possible based on the extrapolation of the course of relations $\varepsilon(t)$ in the selected time range:

$$t = b\sqrt[m]{\frac{\varepsilon_1}{\varepsilon_0}} \tag{5}$$

Results

Based on the equation (2) one may create a mathematical model of the object with the sizes of mushrooms, which enables tracing its behaviour in the set load conditions. Figure 1 presents the set of relations course between the strain values determined with empirical manner σ_{obl} and a relative deformation ε for two selective groups of mushrooms of one crop. One may notice that interim strength is higher at the load in the direction along the stem (axial) not depending on the size of a mushroom.

Calculation results of average values of moduli and indices which characterize mechanical properties of a specimen in particular groups and the selected physical properties were placed in table 1. On account of the dimension diversity resulting from the ellipsoid shape of a mushroom, the level of deformation $\varepsilon = 0{,}15$, identical for both load directions was determined.

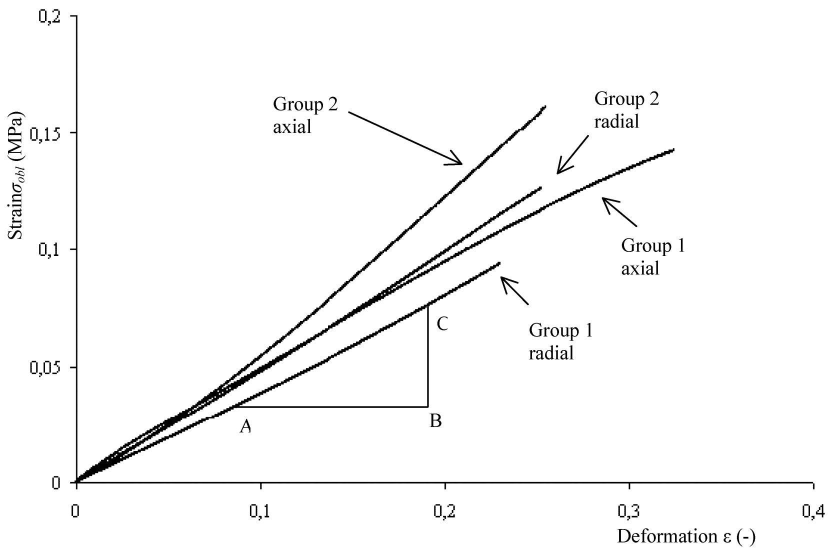

Figure 1. Exemplary set of courses $\sigma_{obl} - \varepsilon$, strength test of mushrooms

Table 1

Average values of the selected physical properties of the investigated mushrooms at the level of deformation $\varepsilon = 0{,}15$ measured during the strength test

Parameter	Selection groups and the direction of load					
	Group 1 axial (SD)	Group 1 radial (SD)	Group 2 axial (SD)	Group 2 radial (SD)	Group 3 axial (SD)	Group 3 radial (SD)
Mass (g)	7.1 (1.20)	8.7 (1.31)	17.1 (3.65)	16.7 (2.38)	16.0 (2.64)	16.6 (0.84)
Moisture (%)	93.6 (0.49)	93.4 (0.49)	92.6 (0.49)	93.2 (0.75)	92.6 (0.49)	94.0 (0.63)
Density (kg·m^{-3})	894 (51.6)	895 (25.4)	845 (69.7)	882 (29.7)	811 (21.9)	826 (42.5)
W_p (J·kg^{-1})	6.47 (0.45)	4.23 (0.66)	7.26 (0.51)	4.75 (0.73)	7.51 (1.09)	3.66 (0.30)
E_c (MPa)	0.51 (0.03)	0.34 (0.06)	0.54 (0.05)	0.37 (0.07)	0.54 (0.09)	0.27 (0.03)

SD – standard deviation

Based on the results set in table 1 one may state that the values of index W_P which characterizes work of deformation inputs are almost two times higher at the axial load than in the radial direction. Similar relation concerns the value of the E_C modulus, which proves the higher mechanical resistance during compression of mushrooms in this direction.

For verification of these relations the obtained results based on the strength test were subjected to statistical processing in the form of a non-parametric test of U Mann-Whitney at the level of significance α= 0.05. The results of analysis were set in table 2.

Table 2
The set of results of the statistical test of correlation of the selected parameters and the direction of the load during the strength test

Parameter	U	p
W_p (J·kg^{-1})	10.000	0.000412
E_c (MPa)	10.000	0.000401

The obtained results confirmed a hypothesis on the significance of the relation of the value of moduli *Wp* and *E*c on the direction of the load application. No impact of the mushroom size on the obtained results was determined.

The test of hysteresis enables assessment of behaviour of mushrooms in conditions simulating changes of loading at the performance of technological processes during the crop and transport. Results of the hysteresis test presented in table 3 concern a cyclic load to obtaining identical level of force corresponding to 40% of the interim strength for a given load direction.

Table 3
Average values of deformation ε, of W_P index and modulus E_C of mushrooms in conditions of cyclic load

Hysteresis	Parameter	Selection groups and the direction of load					
		Group 1 axial (SD)	Group 1 radial (SD)	Group 2 axial (SD)	Group 2 radial (SD)	Group 3 axial (SD)	Group 3 radial (SD)
1 loop load	ε (-)	0.08 (0.02)	0.11 (0.02)	0.09 (0.01)	0.11 (0.01)	0.09 (0.01)	0.11 (0.03)
	W_p (J·kg^{-1})	1.58 (0.39)	2.29 (0.52)	2.25 (0.26)	2.15 (0.28)	2.51 (0.51)	2.25 (0.51)
	E_c (MPa)	0.54 (0.15)	0.37 (0.03)	0.54 (0.09)	0.31 (0.01)	0.52 (0.06)	0.28 (0.04)
1 loop unload	ε (-)	0.04 (0.01)	0.05 (0.01)	0.05 (0.01)	0.07 (0.01)	0.05 (0.01)	0.06 (0.01)
	W_p (J·kg^{-1})	0.69 (0.14)	0.85 (0.10)	1.07 (0.14)	1.02 (0.10)	1.15 (0.17)	0.95 (0.17)
	E_c (MPa)	0.79 (0.18)	0.61 (0.06)	0.70 (0.16)	0.40 (0.02)	0.70 (0.11)	0.39 (0.06)
3 loop load	ε (-)	0.04 (0.01)	0.05 (0.01)	0.05 (0.01)	0.07 (0.01)	0.05 (0.01)	0.08 (0.03)
	W_p (J·kg^{-1})	0.89 (0.18)	1.13 (0.14)	1.38 (0.17)	1.33 (0.15)	1.50 (0.24)	1.27 (0.24)
	E_c (MPa)	0.94 (0.19)	0.76 (0.08)	0.87 (0.18)	0.52 (0.02)	0.85 (0.13)	0.42 (0.16)
3 loop unload	ε (-)	0.04 (0.01)	0.05 (0.01)	0.05 (0.01)	0.06 (0.01)	0.05 (0.01)	0.06 (0.01)
	W_p (J·kg^{-1})	0.68 (0.14)	0.83 (0.09)	1.05 (0.13)	0.98 (0.09)	1.14 (0.17)	0.91 (0.16)
	E_c (MPa)	0.82 (0.18)	0.65 (0.07)	0.73 (0.16)	0.43 (0.02)	0.72 (0.12)	0.41 (0.06)

SD – standard deviation

Relation of the value of modulus W_P on the size of mushrooms and the direction of placing load can be reported. Values of coefficient *E*c depend only on the direction of loading. These relations occur both during the load as well as unloading of a mushroom irrespectively on the order of the cyclic load loop.

Non-parametrical U Mann-Whitney test at the significance level α= 0.05 was used for verification of the reported relations. Results of calculations were set in table 4.

Table 4
The set of results of the statistical test of correlation of the selected parameters and the direction of the load during the strength test

Dimension group	Factor	Parameter	U	P
Group 1	1 loop/3 loop	W_p (J·kg^{-1})	145.000	0.1400421
		E_c (MPa)	81.0000	0.001349
	Load/unload	W_p (J·kg^{-1})	36.0000	0.000010
		E_c (MPa)	163.0000	0.323482
	Direction	W_p (J·kg^{-1})	128.0000	0.053104
		E_c (MPa)	111.0000	0.016669
Group 2	1 loop/3 loop	W_p (J·kg^{-1})	133.0000	0.072046
		E_c (MPa)	106.0000	0.011433
	Load/unload	W_p (J·kg^{-1})	15.0000	0.000011
		E_c (MPa)	199.0000	0.989209
	Direction	W_p (J·kg^{-1})	178.0000	0.0560852
		E_c (MPa)	22.0000	0.000002
Group 3	1 loop/3 loop	W_p (J·kg^{-1})	132.0000	0.067869
		E_c (MPa)	129.0000	0.048214
	Load/unload	W_p (J·kg^{-1})	37.0000	0.000011
		E_c (MPa)	169.0000	0.409356
	Direction	W_p (J·kg^{-1})	135.0000	0.081033
		E_c (MPa)	11.0000	0.000001

Based on the statistical analysis, no significant impact of the direction of the load application and the order of the hysteresis loop cycle on the change of the index value *Wp* in all researched groups of mushrooms was determined. The phase of performance of the hysteresis loop did not significantly affect the changes of the modulus *Ec* value in all the investigated groups. In the remaining analysed cases in all dimension groups correlations with the considered factors were significant.

Possibilities of storing for a longer period may be estimated based on the creep test. The basis for estimating strength to long-lasting storage in the set conditions of load during storage is an effort hypothesis, according to which excessive deformation is treated as a reason for infringing the continuance of the structure of the mushroom trama.

The essence of the issue was presented in figure 1. Point A corresponds to strain at the level of 40% of the interim strength. As a result of the plastic flow during the creep test at the constant value of load, deformation increases its value twice to the level determined with point B. According to the accepted hypothesis, it corresponds to obtaining the condition which corresponds to the value of strain in point C in figure 1.

Table 5 presents average values of coefficients of equation (5) and a predicted time of obtaining doubled value of the initial deformation.

Table 5
Estimation of the storage time of mushrooms in the set load conditions

Parameter	Selection groups and the direction of load					
	Group 1 axial (SD)	Group 1 radial (SD)	Group 2 axial (SD)	Group 2 radial (SD)	Group 3 axial (SD)	Group 3 radial (SD)
m (-)	0.071 (0.01)	0.043 (0.01)	0.049 (0.02)	0.046 (0.01)	0.062 (0.02)	0.048 (0.01)
b (-)	4.59 (1.42)	5.67 (1.88)	2.34 (0.09)	4.29 (0.35)	1.74 (0.22)	1.74 (0.22)
t (days)	1.4 (0.7)	> 365	51 (26)	220 (100)	1.5 (0.44)	105 (87)

SD – standard deviation

Based on the results presented in table 5, one may state that at the load in the axial direction at the level of 40 % of interim strength, there is a high probability that in a short time, a loss of continuance of the mushroom structure may occur. In the set presented in figure 1, it may be seen that at the axial load, mushroom are characterised with a greater strength to the load than in the radial direction, which suggests the possibility of increasing the load during storage of mushrooms e.g. through the increase of the height of the layer of storage. However, such proceedings lead to speeding up the plastic flow phenomenon which may affect deterioration of the product quality.

Conclusion

Interim strength and the modulus of elasticity of a mushroom are strictly related to the direction of applying outside forces and sizes of its pileus. Anisotropy of mechanical properties of a mushroom results also from diversity of work of deformation inputs and is expressed with diversity of the value of the index *Wp* od 7 $J \cdot kg^{-1}$ at the axial load, parallel to the axis of the stem to 3 $J \cdot kg^{-1}$ in perpendicular direction (radial). Values of this index depend on the mushroom sizes. Ability to accumulate energy of elastic deformation during cyclic loads is at the level of 50% work of deformation inputs and it does not depend on the direction of the load application. Anisotropy of mechanical properties of mushrooms may be a significant impact on the time of storing mushrooms. Based on the simulation which was carried out, it was proved that at the load at the level of 40% of interim strength, a predicted time of storing may be shortened to few days. Increased admissible pressures for axial direction are the reason, which may result in the increase of susceptibility to plastic flow at the longer storage of this raw material and in consequence with deterioration of the quality.

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ANIZOTROPIA CECH MECHANICZNYCH OWOCNIKÓW PIECZAREK (*AGARICUS BISPORUS* (J.E. LANGE)IMBACH)

Streszczenie. Badano właściwości mechaniczne i reologiczne owocników pieczarek w grupach selekcjonowanych pod względem kształtu, rozmiarów oraz terminu zbioru. Przeprowadzono próby doraźne, testy histerezy oraz testy pełzania owocników ściskanych między dwiema równoległymi płytami. Obliczono wartości wskaźnika W_P nakładów pracy odkształcenia, współczynnika sprężystości E_C oraz naprężenia σ_{obl}. Określono podatność na pełzanie poprzez obliczenie liczby dni do podwojenia wartości początkowego odkształcenia, na podstawie równania Mac Leoda. Stwierdzono anizotropię cech mechanicznych, w zależności od kierunku obciążenia i rozmiarów owocnika. Współczynnik sprężystości E_C ma wartość rzędu 0,5 MPa przy obciążeniu w kierunku axial oraz 0,3 MPa w kierunku radial, niezależnie od rozmiarów owocnika. Stwierdzono zróżnicowanie wartości wskaźnika Wp od 7 $J \cdot kg^{-1}$ przy obciążeniu w kierunku axial, do 3 $J \cdot kg^{-1}$ w kierunku radial. Zwiększenie nacisków dopuszczalnych dla kierunku axial może być przyczyną ograniczenia czasu składowania tego surowca do kilku dni.

Słowa kluczowe: wytrzymałość, histereza, pełzanie, pieczarki, anizotropia, płyniecie plastyczne

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