PHYSICAL AND MECHANICAL PROPERTIES OF PRECESSED PEA, BEAN, SPINACH AND RADISH SEEDS

FIZIČKE I MEHANIČKE OSOBINE DORAĐENOG SEMENA GRAŠKA, PASULJA, SPANAČA I ROTKVICE

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ABSTRACT

The physical and mechanical properties of pea, bean, spinach and radish seeds, both processed and packaged for sale, were examined under laboratory conditions. The experiment was conducted in order to determine the initial parameters necessary for adjusting the harvester mode so as to reduce the seed damage and losses. Therefore, the results obtained are of immense importance to the selection of appropriate feeds, i.e. the metering mechanism, and setting the operating mode. The following basic physical properties of seeds were measured: dimensions, shape, moisture content, mass of 1000 seeds, the bulk density and the angle of static friction. Mechanical properties were determined by measuring the slope of the load depending on the strain. The slope of the curve load/deflection was determined in three intervals. The first slope of the curve was measured in the area of elastic deformation, the second slope in the area of elastic/plastic deformation, and the third for the rupture point. On the basis of the mean value of the cross-section, the destruction stress and the secant modulus of elasticity were calculated at the point of destruction.

Key words: vegetable seeds, physical properties, mechanical properties, modulus of elasticity, deformation, slope of the curve, rupture force

REZIME

U laboratorijskim uslovima ispitane su fizičke i mehaničke osobine dorađenog i za prodaju zapakovanog semena graška, pasulja, spanaća i rotkvice. Ispitivanje fizičkih i mehaničkih osobina izvedeno je u cilju određivanja polaznih parametara potrebnih za podešavanje režima rada kombajna prilikom mehanizovanog ubiranja u cilju smanjenja gubitaka i oštećenja zrna. Takođe rezultati istraživanja imaju veliki značaj prilikom izbora odgovarajućeg setvenog mehanizma i podešavanja režima rada. Od osnovnih fizičkih osobina izmerene su dimenzije i na osnovu njih određen je oblik, a takođe izmerena je i vlažnost zrna, masa 1000 zrna, nasipna gustina i statički ugao trenja. Mehaničke osobine, određene su merenjem nagiba krive opterećenja u zavisnosti od deformacije. Nagib krive opterećenje/deformacija određen je u tri intervala. Prvi nagib krive izmeren je u oblasti elastične deformacije, drugi nagib krive u oblasti elastične i plastične deformacije, a treći za rupture point. Na osnovu srednje vrednosti poprečnog preseka izračunate su vrednosti za napon razaranja i sekantni modul elastičnosti u tački razaranja.

Ključne reči: seme povrća, fizičke osobine, mehaničke osobine, modul elastičnosti, deformacija, nagib krive, sila razaranja.

INTRODUCTION

From a technical perspective, the knowledge about the basic physical and mechanical properties of seeds is of great importance to constructing the appropriate devices and equipment for seed sowing, harvesting, transporting and dressing with minimal seed damage (Lončarević *et al*, 2010).

Mechanical properties of agricultural materials are tested using methods similar to those used for testing technical materials, namely tensile loading, compression, shear, bending and twisting (Babić, 1994). However, when testing agricultural materials is not possible to create a standard "tube", but special seeds must be tested in their original form. This approach requires taking into account all relevant influencing factors in order to obtain valid results that apply only to the specified conditions. To obtain statistically valid results, measurements must be performed with an appropriate number of repetitions for measurement error reduction.

There are a large number of tests for the determination of mechanical properties, and compression tests are the most commonly used (Mohsenin, 1980). By performing mechanical property testing, the modulus of elasticity and rupture force can be determined. An analysis of the loading/deformation dependence in the area of a lower loading value, for agricultural and mechanical materials, indicates equal and linear dependencies that can be defined by the Hooke's law.

The compression test can be performed in two manners: non-destructive and destructive. The non-destructive test is performed for small deformations, wherein it must be ensured that there are no fractures, breaking, or any other irreversible sample damage. This type of test imitates the squeezing of food in the hand. The problem of determining the modulus of elasticity arises from the fact that the cross-section of seeds during the load increment changes. The force can be precisely determined, but the cross-section must be modelled on the basis of the shape and dimensions of each seed separately. Bourne (1980) lists the equations for calculating the apparent modulus of elasticity for a non-destructive compression test based on the proposal of the American Society of Agricultural Engineers. The sample can be loaded in four manners: parallel or single plate contact, and spherical indenter on curved or flat surface. To calculate the apparent modules of elasticity, it is necessary to determine the deformation, poisson's ratio, force, radii of curvature at the point of contact, and the corresponding coefficients that depend on the load method.

Destructive compression tests result in irreversible damage to the sample. Destructive tests are used for an instrumental profile analysis. Due to the fact that agricultural materials have a non-linear dependence at high loads, it is possible to define several moduli of elasticity (Mohsein, 1980):

- apparent tangent modulus of elasticity defined by Hooke's law (Young's modulus),

- secant modulus of elasticity and
- tangent modulus of elasticity.

Pressing seeds in one direction leads to deformations of other two dimensions. At a poisson's ratio of 0.5, there is no change in volume. Lower coefficient values are associated with volume decreases (Bourne, 1980).

The moisture content of agricultural materials has an impact on the value of the modulus of elasticity. Higher values of the pea seed moisture content caused a decrease the modulus elasticity of the seed tested (Kaifas, 1984). The same dependence was obtained for wheat seeds by Babić et al. (2011), corn seeds by Babić et al. (2012), and for sunflower seeds by Selvam et al. (2014).

For packing and precise sowing of vegetable seeds, it is extremely important that the seed is extremely uniform with regard to the basic physical and mechanical properties (shape, size, and mass of each seeds) (Đukanović et al., 2008).

The purpose of this research is to measure the basic physical and mechanical characteristics of seeds of vegetable crops in order to select the appropriate moment and harvesting mode, as well as machine and processing equipment for minimizing seed losses and damage. The testing was carried out on seed material prepared for sowing, and the basic guidelines for preparation and adjustment of seeding machines were obtained.

MATERIAL AND METHOD

The experiments were carried out at the Laboratory for Biosystems Engineering, the Department of Agricultural Engineering, the Faculty of Agriculture, Novi Sad. The processed and packaged pea, bean, spinach and radish seeds were obtained from the Institute of Field and Vegetable Crops, Novi Sad. Table 1 and Nomenclature present the equipment and apparatuses used in the study to determine the basic physical and mechanical properties.

Table 1. Measurement equipment used in the research process

Measured quantities and units	Name of equipment, manufacturer, model	Measurement range, resolution, accuracy instrument
Dimensions of seed (mm)	Caliper, TMA INOX, D-6-1, Germany	0-200 mm; 0.1 mm; ±0.05 mm
Mass (g)	Analytical scale, KERN PLJ360-314, Germany	0-200 g, 0.001g, ±0.002 g
Volume of sample (cm ³)	Glass measuring cylinder Plastic measuring cylinder	500 ml; 10 ml; ±5 ml 20 ml; 2 ml; ±1 ml
Mechanical properties (N), (mm/s),	TMS PRO, Food Technology Corporation, Virginia, USA	±2500 N, 0.015%
Static friction angle, (°)	The steep plane for friction coefficient determining	0-90°; 1°; ±0.5°
Moisture content, (% _{wb})	Laboratory dryer Sterimatic ST-11 "Instrumentarija", Zagreb	0–200 °C; ±5 °C

Nomenclature:

f – index of seed shape (-),
 l – length (mm),
 w – width (mm),
 t – thickness (mm),
 D_a (mm) – arithmetic mean diameter,
 D_g (mm) – geometric mean diameter,
 Ψ – sphericity (-),
 Δl – absolute deformation (mm),
 ε – relative deformation (-),
 σ – normal stress (N/mm²),
 E – secant modulus of elasticity (N/mm²),
 F_r – rupture force (N),
 l_1 – slope curve in interval 1 (N/mm),
 l_2 – slope curve in interval 2 (N/mm),
 l_3 – slope curve in interval 3 (N/mm),
 m – mass of sample (kg, g),
 m_0 – mass of sample before drying (g),
 m_1 – mass of sample after drying (g),
 m_{1000} – mass of 1000 seeds (g),
 ρ_n – bulk density (kg/m³),
 α_s – angle of static friction (°),
 μ_s – static friction coefficient (-),
 ω_{wb} – moisture content on wet basis (%_{wb}),
 V – volume of sample (m³),
 A_{mean} – the mean cross-sectional area of seed (mm²),
 A_{max} – the maximum cross-sectional area of seed (mm²).

Method of work

Seed dimensions were measured using a caliper. On the basis of the random sample method, a total of 30 seeds were selected for measurement. The length (l), width (w) and thickness (t) of each seed were measured. Length was the largest measured dimension, the width was the largest dimension normal to the direction of the length measurement, and the thickness was the largest dimension normal to the direction of the length and width measurements. The geometric mean diameter D_g was measured using Equation 1 (Babić and Babić, 2000, Ponjičan et al, 2017):

$$D_g = (l \cdot w \cdot t)^{1/3}, (\text{mm}) \quad (1)$$

Arithmetic mean diameter D_a Equation 2:

$$D_a = \frac{(l + w + t)}{3}, (\text{mm}) \quad (2)$$

Sphericity Ψ , Equation 3:

$$\Psi = \frac{D_g}{t}, (-) \quad (3)$$

On the basis of the ratio of length, width and thickness, according to ISO 5691-1981 (E), the shape of the seeds were defined according to Equation 4:

$$f = \frac{l^2}{w \cdot t} \cdot 100, (-) \quad (4)$$

For all four types of seeds (beans, peas, radish and spinach), 1000 seeds were counted. The mass of a 1000 seeds was measured using an analytical balance with a precision of ± 0.001 g. Bulk density was determined using an analytical balance (mass, m) and a graduated measuring cylinder (sample volume, V). Bulk density was calculated on the basis of Equation 5:

$$\rho_n = \frac{m}{V}, (\text{kg/m}^3) \quad (5)$$

The angle of static friction was determined using a device featuring a flat metal surface on the upper end, on which the

seeds were placed. The device has a handle disposed on the back side, allowing a gradual increase in the angle. There is also a measuring scale fitted on the side, which serves to read the angle of static friction (α_s). The appropriate angle was reached when about 2/3 of the material started to slide down from the metal surface. The slope of the plate represents the value of the angle of static friction (α_s) and was read directly from the device, and the friction coefficient μ_s was calculated using Equation 6:

$$\mu_s = \tan \alpha_s$$

The moisture content of the samples was determined using the thermogravimetric method (*Službeni list*, 1983). The following equipment was used for moisture content measurements: an analytical balance with accuracy of ± 0.001 g, metal stainless steel vessels, a fan dryer and a glass bell with silica gel. The mass of chopped samples of 3 g to 5 g was placed in the oven at a temperature of 105 °C and dried for 1 hour, after which it was removed from the dryer and placed in a glass bell to cool. Mass measurements were performed subsequently, after which the bowl was returned to the dryer and the procedure was repeated until the masses of the two successive measurements were equal. The moisture content of the sample ω was calculated using Equation 7:

$$\omega_{wb} = \frac{m - m_1}{m} \cdot 100,$$

Fig. 1. Mechanical properties of vegetable seeds—compression test

For the determination of the mechanical properties of the seed samples, a compression test was performed using the TMS PRO with the TLPro supporting software. For each type of seed, a total of 20 samples were measured. The seed selection was carried out using the method of random selection. The tested seed material (beans, peas, radish and spinach) was placed on the plate, where the pattern was applied to the plate by force. During measurements, a measuring cell of 500 N range was used with a measuring speed of 30 mm/min. The end of the measurement was determined according to the magnitude of deformation. The dependence between load and deformation over time was recorded in the computer database (Figure 1). After recording, a data analysis was performed using the TLPro software package, which is compatible with Microsoft Office Excel.

The following mechanical properties were measured and calculated: the force at the moment of destruction (rupture point), the absolute and relative deformation at the moment of destruction, the moment of destruction, the secant modulus of elasticity at the rupture point, and the curvature of the curve at the intervals listed in Table 2.

Table 2. Definition of slope curve intervals depending on the type of seeds

	l_1 (N/mm)	l_2 (N/mm)	l_3 (N/mm)
Pea	0.1 - 0.2	0.5 - 0.6	0 - 0.84
Bean	0.05 - 0.1	0.3 - 0.35	0 - 0.47
Spinach	0.1 - 0.15	0.4 - 0.5	0 - 0.49
Radish	0.1 - 0.15	0.25 - 0.35	0 - 0.42

For each type of seeds, three slopes of the curve l_1 , l_2 , and l_3 were determined. The slopes of the curve were in the following areas: the area of elastic deformation (first), the area of elastic/plastic deformation (second), and at the rupture point of seeds (third).

The maximum cross-sectional area of seed A_{max} was calculated according to their dimension (l and w), and was approximated as an ellipsoid (*Lončarević*, 2011).

$$A_{max} = \frac{l \cdot w \cdot \pi}{4}, (\text{mm}^2) \quad (8)$$

The mean cross-sectional area of seed A_{mean} was calculated using Equation 9 (*Lončarević*, 2011):

$$A_{mean} = \frac{l \cdot w \cdot \pi^3}{64}, (\text{mm}^2) \quad (9)$$

Statistical data processing was performed using the Statistica and Microsoft Office Excel software packages. A correlation analysis of the parameters measured was carried out and their average value and standard deviation were determined.

RESULTS AND DISCUSSION

On the basis of the measured seed dimensions (length, width, height), the geometric and volume diameters were calculated. As the seed material used was previously calibrated, low values of the standard deviation relative to the measured average values were determined. On the basis of the values measured for the index of shape, the pea seeds featured a round shape, the bean seeds featured a very long shape, the spinach seeds featured an oval or round shape, and the radish seeds featured a long to oval shape (ISO 5691). The measured seed parameters (namely dimensions, diameter and shape of seeds) are of immense importance to the construction and selection of the appropriate type of metering machinery for precise and quality sowing.

Table 3. Dimensions, diameters, index of sphericity, shape and maximum and mean cross-sectional area of vegetable seed

	l (mm)	w (mm)	t (mm)	Dg (mm)	Da (mm)	Ψ	f (-)	A_{max} (mm ²)	A_{mean} (mm ²)
Pea	7.05 ±0.16	6.47 ±0.18	6.03 ±0.17	6.50 ±0.12	6.52 ±0.12	1.08 ±0.02	128.34 ±8.70	35.83 ±1.42	28.08 ±0.88
Bean	12.97 ±0.31	7.25 ±0.18	5.83 ±0.23	8.18 ±0.18	8.68 ±0.18	1.41 ±0.04	401.34 ±22.83	73.95 ±3.09	45.57 ±1.91
Spinach	3.58 ±0.20	3.26 ±0.13	2.21 ±0.10	2.95 ±0.13	3.02 ±0.13	1.34 ±0.03	178.98 ±13.06	9.23 ±0.82	5.68 ±0.50
Radish	3.01 ±0.12	2.50 ±0.16	1.79 ±0.08	2.38 ±0.09	2.44 ±0.09	1.33 ±0.05	204.95 ±12.67	5.95 ±0.56	3.67 ±0.34

Table 4. Moisture content, mass of 1000 seeds, bulk density, static friction coefficient

	ω_{wb} (%)	m_{1000} (g)	ρ_n (kg/m ³)	α_s (°)	μ_s (-)
Pea	7.561	181.88	821.27±12.48	15.20±0.29	0.271±0.01
Bean	8.836	333.09	832.21±22	13.80±0.58	0.25±0.01
Spinach	2.195	9.40	504.77±8.68	19.60±0.21	0.356±0.004
Radish	1.039	7.10	709.00±11.63	18.30±0.22	0.331±0.004

Table 5. Correlation coefficients for pea seed mechanical properties

Variable	Mean	Δl (mm)	σ (N/mm ²)	ε (-)	E (N/mm ²)	l_1 (N/mm)	l_2 (N/mm)	l_3 (N/mm)
Fr (N)	251.43±57.47	0.85	1.00	0.85	0.95	0.10	0.78	0.95
Δl (mm)	0.84±0.10	-	0.85	1.00	0.65	-0.05	0.63	0.65
σ (N/mm ²)	11.39±2.60		-	0.85	0.95	0.10	0.78	0.95
ε (-)	0.14±0.02			-	0.65	-0.05	0.63	0.65
E (N/mm ²)	78.81±10.91				-	0.17	0.76	1.00
l_1 (N/mm)	48.81±8.33					-	-0.11	0.17
l_2 (N/mm)	449.95±25.72						-	0.76
l_3 (N/mm)	288.59±39.95							-

Table 6. Correlation coefficients for bean seed mechanical properties

Variable	Mean	Δl (mm)	σ (N/mm ²)	ε (-)	E (N/mm ²)	l_1 (N/mm)	l_2 (N/mm)	l_3 (N/mm)
Fr (N)	88.20±13.04	0.69	1.00	0.69	0.95	0.09	0.74	0.95
Δl (mm)	0.47±0.03	-	0.69	1.00	0.44	-0.06	0.07	0.44
σ (N/mm ²)	1.94±0.29		-	0.69	0.95	0.09	0.74	0.95
ε (-)	0.08±0.01			-	0.44	-0.06	0.07	0.44
E (N/mm ²)	23.63±2.98				-	0.14	0.88	1.00
l_1 (N/mm)	63.73±7.84					-	0.09	0.14
l_2 (N/mm)	306.30±37.93						-	0.88
l_3 (N/mm)	184.68±23.28							-

Table 7 Correlation coefficients for spinach seed mechanical properties

Variable	Mean	Δl (mm)	σ (N/mm ²)	ε (-)	E (N/mm ²)	l_1 (N/mm)	l_2 (N/mm)	l_3 (N/mm)
Fr (N)	33.80±15.85	0.68	1.00	0.68	0.95	0.25	0.94	0.95
Δl (mm)	0.49±0.12	-	0.68	1.00	0.43	-0.37	0.51	0.43
σ (N/mm ²)	5.95±2.79		-	0.68	0.95	0.25	0.94	0.95
ε (-)	0.22±0.05			-	0.43	-0.37	0.51	0.43
E (N/mm ²)	23.90±8.30				-	0.50	0.97	1.00
l_1 (N/mm)	40.52±6.70					-	0.40	0.50
l_2 (N/mm)	92.81±41.32						-	0.97
l_3 (N/mm)	61.42±21.32							-

Table 8 Correlation coefficients for radish seed mechanical properties

Variable	Mean	Δl (mm)	σ (N/mm ²)	ε (-)	E (N/mm ²)	l_1 (N/mm)	l_2 (N/mm)	l_3 (N/mm)
Fr (N)	18.28±2.92	0.46	1.00	0.46	0.76	0.31	0.90	0.76
Δl (mm)	0.42±0.05	-	0.46	1.00	-0.22	-0.20	0.27	-0.22
σ (N/mm ²)	4.98±0.80		-	0.46	0.76	0.31	0.90	0.76
ε (-)	0.24±0.03			-	-0.22	-0.20	0.27	-0.22
E (N/mm ²)	21.13±2.50				-	0.49	0.79	1.00
l_1 (N/mm)	43.15±6.37					-	0.40	0.49
l_2 (N/mm)	50.07±12.99						-	0.79
l_3 (N/mm)	43.33±5.12							-

On the basis of the physical properties recorded, the seed moisture content relative to the wet basis was measured, the mass of 1000 seeds, the seed bulk density, and the angle and coefficient of static friction (Table 4).

Moisture content was extremely low, especially in the spinach and radish seed samples. For volume type seeders, the mass of 1000 seeds is a very useful parameter for calculating the number of seeds sown. The bulk density and static friction coefficient are the parameters that are extremely important in the process of using and constructing seeders, as well as other machinery and equipment for seed processing and storage.

Mechanical properties were determined using a compression test. On the basis of the measured load/deformation ratio, the parameters that are most commonly used for the determination of mechanical properties were measured (Babić et al., 2011; Ponjičan et al., 2012, 2013a, 2013b and 2014; Kwino et al., 2017). Using the correlation analysis, the interdependence between the individual measured and calculated parameters were determined. On the basis of the results of the correlation analysis, it is possible to select and apply the most effective parameters for further testing.

In addition to high values of the rupture force (F_r), normal stress (σ), secant modulus of elasticity (E) and slope curve (l_2 and l_3) recorded, high value of the correlation coefficients were also determined. Low values of the correlation coefficient were determined between the slope of the curve for low values of the absolute deformation (l_1) and the slope of the curve for high values of the absolute deflection (l_2 and l_3) in all four tested seed cultures. Low values of the coefficient of correlation between the deformation (Δl i ε) and the slope of the curve (l_1 , l_2 , and l_3) were determined in the bean, spinach and radish seed samples. According to the data processing software TLPro, the slope of the curve (l_1) is also called the initial modulus of elasticity.

The non-destructive compression test performed in the field best describes the parameter slope of the curve for low absolute deflection values (l_1). For the evaluation of the behaviour of materials using the destructive compression test, other parameters can be used such as the rupture force (F_r) and slope curve (l_2 and l_3) parameters, which are even more complex and take seed deformation into account. Parameters such as stress (σ) and secant modulus of elasticity (E) should be used only if there is a possibility of their precise determination.

The secant modulus of elasticity was calculated on the basis of the mean cross-sectional area (A_{mean}) and had relatively low values compared to other machine materials. The modulus of elasticity values for seeds was in the range of values that were measured for the young modulus of elasticity of PELD, PEHD and PTFE. (http://www.engineeringtoolbox.com/young-modulus-d_417.html).

The mean cross-sectional area of seeds was used for the determination of the stress and the secant modulus of elasticity in this study. With regard to the shape and the reference area calculated, the shape of the vegetable seed was found to be rather ellipsoid.

DISCUSSION

In the literature, there are several ways of determining the reference area on which the external load acts. Babić et al. (2012) lists the whole cross-section of corn seeds as the reference surface area on which the force operates, regardless of the touch surface. In order to compare the results, corn seeds of equal dimensions and shapes were selected. Lončarević et al. (2006) also took into account the entire mean cross-section of peleted sugar beet seeds. Pivnički et al. (2003) and Lončarević et

al. (2010) argue that the reference surface area on which the force acts is equal to the surface at half the height of the half-axis of the ellipse of soybean seeds. Bourne (2002) lists the specific equations for surface modelling that depend on the load method and are the functions of the seeds diameter, the poison's ratio and radii of curvature. Dobrzański and Stepniewski (2013) also present the equations for the modulus of elasticity of bean seed coats. Same authors state that the editing of seeds cracks can be determined using X-ray.

CONCLUSION

The vegetable seeds used in the experiments were uniform in dimension, which was confirmed by low values of the coefficient of variation. Pea seed is round, bean seed is very elongated, and spinach and radish feature an oval shape. Using the compression test, a great interdependence between the rupture force, the secant modulus of elasticity at rupture point and the slope of the curve for higher loads was determined. The slope of curves in the field of the elastic deformation exhibited low values of the correlation coefficients relative to the other measured and calculated parameters. The stress and secant modulus of elasticity was calculated in the compressed area measured at the moment of rupture. It is the starting parameter in the process of designing and selecting the operating mode of seeding and harvesting machines, as well as processing equipment.

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