TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE – 2013, Vol. 13, No. 1, 109–112

Effect of water content on the strain hysteresis of pea (*Pisum S.*)

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Received December 16.2012; accepted March 14.2013

Summary. The paper presents results of tests on influence of pea moisture on parameters obtained in a test of axial loading and unloading. For the tests pea cv. Fidelia at the moisture ranging from 8 to 18% was used. The measurements were performed on a universal machine Zwick Z020. The load-displacement characteristics recorded using the TestXpert software by Zwick allowed to set out values of elastic and loss energies and corresponding deformations. An increase in seed moisture caused changes in values and relations between the aforementioned parameters. The lowest changes were observed for the elastic strain energy, which changed only slightly with the change of seed moisture. A considerable increase was observed for the lost energy, which also had significant influence on values of the total energy. Similar relations were found while analysing seed deformations.
Key words: compression, hysteresis, moisture, pea

INTRODUCTION

The great interest in studying of mechanical properties of food and agricultural materials is reasoned by fact that the latter have a crucial impact on conditions and outcomes of processing as well as properties of final products. Agricultural materials frequently discover a large variability in the response to mechanical loading. They change from brittle to elasto-plastic, plastic, viscous due to varying moisture, temperature, ripeness, and others [4, 10, 20]. Grace to this, on one hand a large spectrum of products can be obtained and on the other hand strict control of processing conditions is necessary for the optimization of outcomes.

Mechanical properties in relation to their processing and quality is an issue that has been studied with different approaches for years. Within the context, research on a material's elastic or plastic behaviour is one of the most important. Strain hysteresis is one of the available techniques, and addresses the amount of energy dissipated in the loaded body due to friction, internal damage, irreversible deformations etc. [1,7,13]. Thus, it can be used for description of the processes, for which such exchange is relevant. It can be related to a material's resistance to cracking [5,18], susceptibility to reversible deformations and internal damages, grindability and others [2]. Increased plasticity significantly influences breakage mechanisms, which leads to an increase in grinding energy requirements [3,10]. It is necessary in compaction processes, where it causes the agglomerate formation in an easier and more energy-efficient way [8,12,14,15]. In this context, the profound knowledge on materials response to loading is important for agglomeration of foods, feeds, biomass, and others [6,8,9,16,17].

The objective of the study is to focus on examining the effect of moisture content on the response of pea seed to cyclic loading.

MATERIAL AND METHODS

The Polish variety of pea (*Pisum sativum* L.) cv. Fidelia was used in the studies. The moisture content of a batch of seeds sample was determined applying the air oven method and drying three 5 g samples of pre-crushed seeds for over 3 h at a temperature of 105°C according to Polish Standard PN-86/A74011.The batch was subsequently divided into smaller samples, and to each of them, the amount of required water was added (or removed by drying in 40°C) to achieve moisture levels established at 8–18% (wet basis) with 2% increment. The added or removed amounts of water were achieved, according to the mass balance equations. The samples were then tempered in hermetic jars, and stored for 48 hours at ambient temperature.

Testing was carried out on a Zwick Z020 universal testing machine. An intact seed was positioned on the fixed bottom plate, such that the plane splitting two seed cotyledons was parallel to the compressive plates. The seed was then loaded and unloaded with the compression rate adjusted at 10 mm/min. The loading was performed until a predefined force, set at 200N, was achieved. For each test load–displacement data were recorded using testXpert software by Zwick. On the basis of the strain hysteresis loops, an example of which is presented in Fig.1, partitions of strain energy and deformations were calculated (Fig. 1) [11,12,19]. In the figure, *Et* represents the total amount of strain energy absorbed by a seed during compression, while *En-r* and *Er* correspond to the irrecoverable and released energy respectively. All the experiments were done in 10 repetitions for each moisture level of seeds.

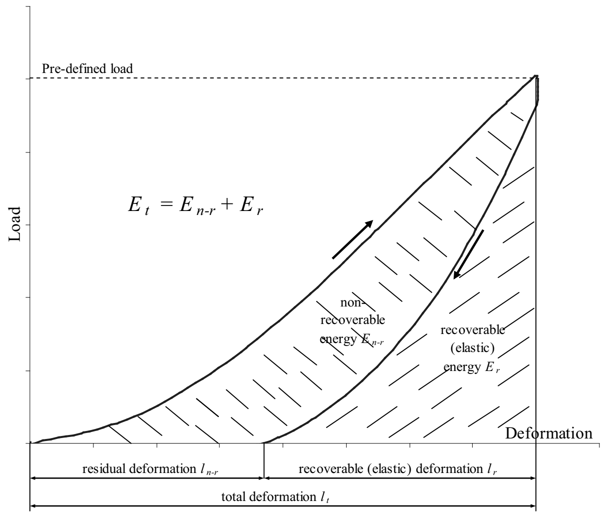

Fig. 1. Typical strain hysteresis curve while loading of a pea seed

Statistical analyses of the obtained parameters were done with a help of Statistica 6.0 software (StatSoft Inc.). Any verification of statistical hypotheses and development of mathematical models were done applying 95% probability level.

RESULTS

General view of the loading-unloading profiles in relation to moisture is given in Fig. 2.

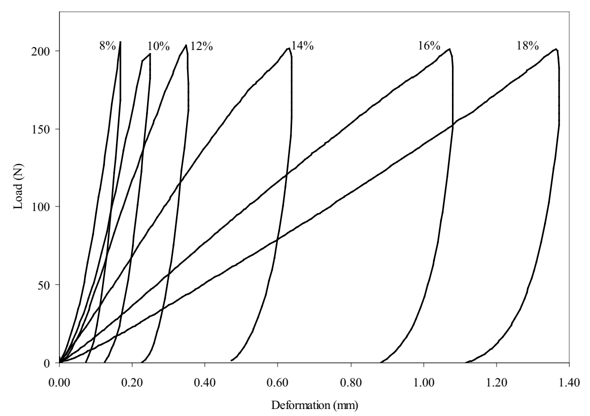

Fig. 2. Examples of hysteresis curves for pea seeds varying in moisture content

It is well noticeable, that the response of an individual seed to the compressive loading was strongly related to the amount of water content. An increase of moisture caused significant changes in the shape of the hysteresis loops. The area enclosed between the loading and unloading parts of the hysteresis curves increased very significantly with the moisture increment. It expresses the increased plasticity of seeds. As the result of it, the response of seed to mechanical loading is prevalently plastic in nature. The strain energy used is mainly released to permanent i.e. non recoverable deformations. They are not accompanied by readable cracking effects, what demonstrates the loss of brittleness and increased toughness of seeds. The results are in agreement with observed for pea [10], and similar to obtained by Łysiak et al. for wheat kernels [11].

A high increase of deformations up to the pre-defined load (200 N) was first and the best visible. The total deformation increased from about 0.20 mm to 1.63 mm. The differences were more considerable for moisture above 12%. This was confirmed by statistical analysis. The analyses applying Tukey procedures discovered that the average deformations obtained for the particular moisture levels were significantly different at 95% probability. It was observed that the increase in total deformation was mainly driven by the level of the permanent one. The latter increased in similar extent from 0.09 to 1.37 mm. The two were closely correlated. The elastic deformation increased with moisture as well, but relatively very slightly (Fig. 3).

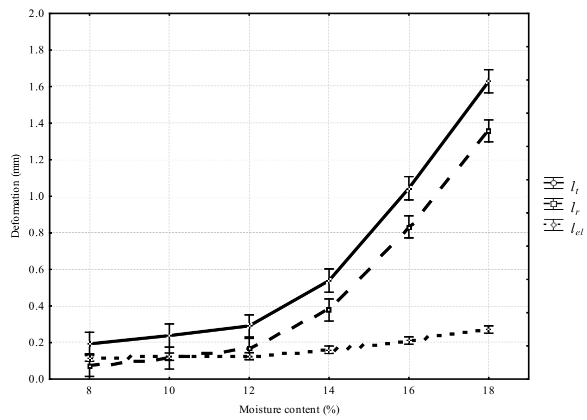

Fig. 3. Influence of seed moisture on values of total, elastic and lost deformations

Moisture content influenced the relative contribution of residual deformation in relation to elastic one (Fig. 4). The share of residual (permanent) deformation increased from 39% up to 83% in the studied moisture range. It was observed that the rate of the increment was higher at lower moisture levels, and slightly decreased above 14-16%. The differences were statistically confirmed at 95% probability.

The above analyzed total, residual and elastic deformations were expressed in function of seed moisture. It was done by means of regression equations and procedures included in a Statistica 6.0 software (Statsoft Inc.). The results are presented in table 1. In each case the best fitting to the experimental data was obtained for polynomial equations of the second degree. The right choice of the mathematical models was confirmed by the high values of

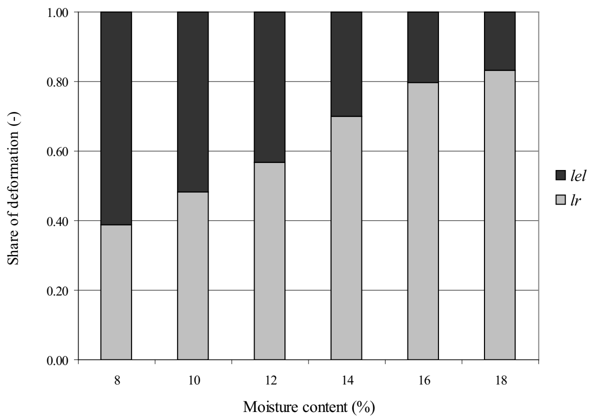

Fig. 4. Share of elastic and permanent deformation as a function of seed moisture

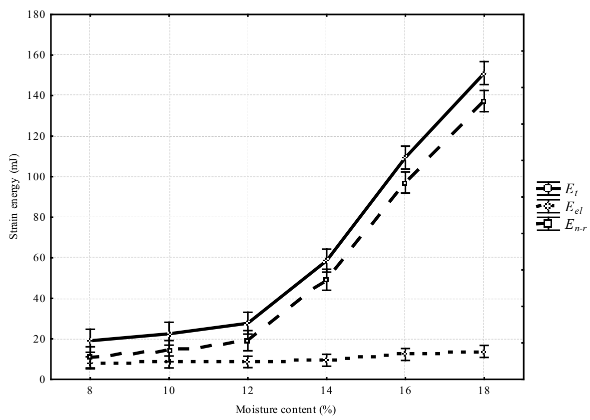

Fig. 5. Influence of seed moisture on values of total, elastic and non-recoverable strain energy

determination coefficients, which were generally higher than 0.99 (on the basis of averages values obtained for particular moisture level)

Table 1. Relations describing the influence of moisture of pea on the deformation during axial loading-unloading

Parameter	Equation form: $y = ax^2 + bx + c$			Determination coefficient R^2
	a	*b*	*c*	
Total deformation, l_t (mm)	0.0201	-0.3826	1.994	0.996
Residual deformation l_r (mm)	0.0180	-0.3438	1.696	0.996
Elastic deformation l_{el} (mm)	0.0021	-0.0388	0.297	0.996
Share of residual deformation (-)	-0.0009	0.0714	-0.137	0.985

x – moisture of pea seeds in % (w.b.)

The effect of moisture on the energies obtained in the hysteresis test was similar to the described above changes in deformations (Fig. 5 and 6). The total strain energy increased from about 20 mJ to 152 mJ. The relatively low increment for the lower moisture range (8-12%) was followed by a considerable increase for the moisture above 12%. It was confirmed that the strain energy inputs were mainly dependent on the energy absorbed for plastic deformations. The irreversible energy increased very significantly, from 0.12 mJ to 1.38 mJ.

The elastic energy changed relatively slightly with moisture, although a rise in this parameter was also observed.

The contribution of non-recoverable energy increased very significantly with the increase in amount of water (Fig. 6). The values ranged from 57% to 90%. The magnitude of changes decreased when moisture crossed 14-16%. The differences were statistically confirmed at 95% probability.

Similarly to the analyses done for the deformations, the strain energy release during the axial loading-unloading was related to the moisture of pea seeds. The results are presented in table 2. The best fitting to the experimental data was also obtained for polynomial equations of the second degree.

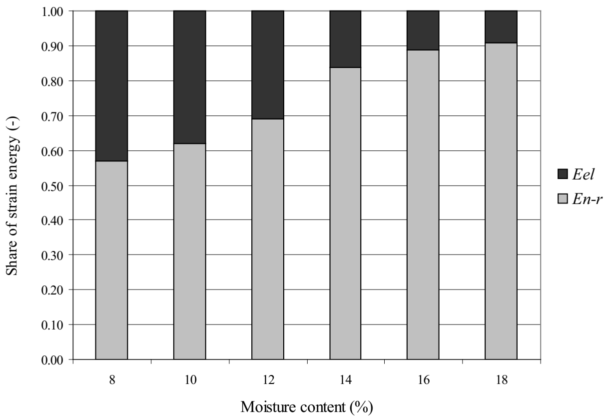

Fig. 6. Share of elastic and permanent energy as a function of seed moisture

The obtained relations were, like previously, characterized by high values of determination coefficients.

Table 2. Relations describing the influence of moisture of pea on the strain energy release during uniaxial loading-unloading

Parameter	Equation form: $y = ax^2 + bx + c$			Determination coefficient R^2
	a	*b*	*c*	
Total strain energy, E_t (mJ)	1.668	-29.77	150.4	0.992
Non-recoverable strain energy E_{n-r} (mJ)	1.592	-28.38	135.8	0.991
Elastic strain energy E_{el} (mJ)	0.0754	-1.387	14.56	0.968
Share of non-recoverable strain energy (-)	-0.0011	0.0657	0.0902	0.9548

x – moisture of pea seeds in % (w.b.)

CONCLUSIONS

1. The differences in water content of seeds were clearly reflected by changes in parameters obtained during cycling loading.
2. The studied increment in moisture resulted in an increase in elastic, permanent and total deformations. The most

significant influence was observed for the residual deformation.

3. The elastic energy changed only slightly with the rise in seed moisture. On the other hand, a considerable increase of the energy absorbed by irreversible processes was observed. It had a major influence on the total strain energy inputs during compression.
4. The share of non-reversible energy and deformation changed significantly with the seed moisture. The effect was observed mainly at lower moisture range.
5. The influence of moisture of pea on the parameters obtained during axial loading-unloading were the best described with the help of polynomial equations of the second degree. It concerns both analyzed deformation and strain energies.
6. The strain hysteresis data will be correlated to grinding and agglomeration, and are expected to be useful for a better understanding of the phenomena accompanying these processes. This is necessary both for of successive energy optimization and improving production quality.

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WPŁYW WILGOTNOŚCI NA HISTEREZĘ ODKSZTAŁCEŃ NASION GROCHU (*PISUM S.)*

Streszczenie: W pracy przedstawiono wyniki badań nad wpływem wilgotności grochu na parametry uzyskane w wyniku osiowego cyklicznego ściskania. Do badań zastosowano groch odmiany Fidelia o wilgotności w zakresie 8-18%. Badania wykonano na uniwersalnej maszynie wytrzymałościowej Zwick Z020. Na podstawie eksperymentalnych charakterystyk siła-przemieszczenie, uzyskanych przy wykorzystaniu oprogramowania TestXpert firmy Zwick, określono wartości nakładów energii sprężystej, trwałej i całkowitej oraz odpowiadające im deformacje nasion. Wzrost wilgotności nasion powodował wyraźne zmiany w wartościach i wzajemnych relacjach pomiędzy analizowanymi parametrami. Najmniejsze zmiany obserwowano dla nakładów energii sprężystej, które w badanym zakresie wilgotności zmieniały się jedynie nieznacznie. Znaczący wzrost ze zwiększaniem wilgotności nasion odnotowano dla energii odkształceń trwałych, która też wywierała zasadniczy wpływ na wartość energii całkowitej. Podobne zależności stwierdzono w analizach oddziaływania wilgotności na wartości deformacji nasion.

Słowa kluczowe: ściskanie. histereza, wilgotność, groch