AGROPHYSICAL PROPERTIES OF LENTIL (*Lens culinaris* Medik.)

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in Sustainable Agriculture AGROPHYSICS

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CONTENTS

1. INTRODUCTION

1.1. Origin, history, general features

Lentil (*Lens culinaris* Medik.) belongs to the highly numerous family of papilionaceous plants (*Fabaceae=Papilionaceae*), comprising approximately 18 000 species [46]. Historical records as well as reports in natural literature permit the plant to be included among the oldest grown by man. The species probably originates from the Middle East. In Central Asia it was grown as far back as about five thousand years before Christ. There is historical evidence that lentil was grown in the Mediterranean – in Greece and in Egypt. It was consumed in the form of seeds or of bread baked from lentil flour [25]. Lentil is mentioned in the Bible, in the Book of Genesis, where an attempt is described of trading the right of first birth for a bowl of lentils. In the Arab countries, lentil was often the basic food and its cultivation continues in India, Egypt, Algeria, Pakistan, Syria, Bangladesh, Turkey, Russia, and other CIS countries. According to FAO, in the years 1990-1992 the world total of lentil cultivation areas was 1.3 million hectares, with a tendency to increase, and at the end of the nineteen nineties it reached 3 million hectares. At present major lentil seed producing countries include India (1.2 million ha) and, on a smaller scale, Turkey, Pakistan, Lebanon, Iran, USA, and Canada. In Europe the country with the largest lentil growing area is Spain (40 thousand ha). Lentil is also popular in Greece, Bulgaria and Slovakia. The crop yields of lentil are varied – 0.5 t ha^{-1} (Turkey), 0.77 t ha^{-1} (India), 1.56 t ha^{-1} (France), 2.05 t ha^{-1} (Lebanon) [14,15]. An increased interest in lentil on the world scale has been observed since the beginning of the nineteen eighties, as evidenced by the development of both fundamental and applied research conducted at renowned research centres in Canada (University of Saskatchewan), USA (Washington State University) and in other countries [37]. The increased interest resulted from the high opinion on lentil's usable value and has been strengthened by the notable increase in the population of Asia and Africa, i.e. areas with the highest index of lentil consumption. In highly developed countries, on the other hand, the interest in lentil has been spurred by its exceptional dietary properties for man, and by the high nutritional and sensory values of lentil seeds [2,6]. Interest in the plant follows also from the current fashion for vegetarianism, from the search for alternative or complementary sources of proteins, and from the rediscovery of food products of plant origin. An increase has been observed in the demand for plant proteins, following the reduction in beef consumption due to the discovery, in 1996, of the mad cow disease (BSE). A new application of the typically culinary plant is the consumption of sprouted seeds Whole seeds of brown, green and red lentil are subjected to soaking and germination. Red lentil is brown on the outside and red inside. Sprouts of that lentil have an original spicy taste and are a product well sought after by gourmets. Hard seed varieties (the best) originate from India [48]. Red lentil seeds are also used in the treatment of gastric and duodenum ulcers. In Poland lentil was commonly known in the Middle Ages [25]. Next to the pea, it is the oldest high-protein plant grown in the country [7]. Seeds of edible lentil have been found in the course of excavations at the Biskupin archeological site. Before World War II, lentil was grown in Poland on an area of about 1.400 ha. With the passage of time, that shrank to small areas in house gardens and private plots, primarily in the east and south-east regions of the country [47]. Most frequently, those have been and still are local small-seed populations based on mixtures of small-seed ecotypes. Those local populations may be a genetic source of favourable features [21]. According to Piróg *et al*. [26], Milczak *et al*. [21], there was a lack of Polish varieties that would regularly produce high yields. For many years the breeding of lentil in Poland has been characterized by a high degree of neglect [19]. Over the last decade, the plant has been given back its due position, also in this country. The initiated breeding programs are aimed at producing new high-yield cultivars, based on large-seed biotypes or utilizing e.g. a multipod mutant [20]. An example of a breeding success of the Lublin research centre is the Tina – the first Polish-bred lentil cultivar to be entered, in 1998, in the Register of Original Vegetable Plant Varieties [22]. At present we have two Polish varieties of lentil – Tina and Anita [8]. However, the demand for lentil seed exceeds the supply of Polish-produced lentil and consumption lentil has to be imported from Canada and the USA.

Lentil as a plant has modest soil and fertilization requirements (less demanding than those of the more common consumption pea). It yields the best crops on medium compacted soils from the very good or good rye complex. Due to its tendency to lodge, it should not be grown on sites rich in nitrogen, e.g. with excessive levels of nitrogen content after perennial papilonaceous plants. Under such conditions, lentil plants tend to extend their vegetative development, extend their blooming stage, become overgrown and lodge. This results from the fact that lentil utilizes free nitrogen through symbiosis with *Rizobium leguminosarum* bacteria. The amount of bound atmospheric nitrogen varies within the range of 26-67 kg N ha^{-1} [31]. Heavy soils, waterlogged, are not a good stand for lentil due to the high susceptibility of the plants to fusariosis which cause the serious disease of seedling gangrene [50]. Among the pests occurring on lentil we can mention the snout beetle and the pea aphid. Lentil seeds should be sown in early spring, and the plant is well tolerant of short several-degree spring frosts [1,15]. Seeds germinate hypogeically at the temperature of 3-4^{o}C, and their brief vernalization occurs at the temperature of 5-8^{o}C. Emergence takes place after 6-12 days. Lentil is characterized by exceptional resistance to drought. It has the lowest water requirements among the papilonaceous plants. The insolation conditions in this country are suitable for lentil which requires long periods of daylight. The best conditions for lentil growing are found in the south-eastern part of Poland. The area of lentil cultivation, however, is limited due to the unreliable yielding and to the competition of higher-yielding leguminous plants. Premature pod cracking and seed shedding is the cause of seed crop losses, while seed susceptibility to mechanical damage results in a deterioration of quality. These are significant problems encountered when growing the plant as a crop. Seed losses caused by shedding, as estimated by Sosnowski *et al*. [34], reach up to about 20% of the crop. According to an approximate assessment made by the authors of this text, with single-stage combine harvest at the seed plantation of „Spójnia" – Hodowla I Nasiennictwo Ogrodnicze Spółka z o.o. (Plant Breeding and Horticultural Seed Production Ltd.) in Nochów, the seed losses were considerably higher. According to a study by Sosnowski *et al*. [33] on lentil grown in Slovakia, seed losses with mechanical multi-stage harvesting were on the level of 14.2%. In regions of West Asia and North Africa reported lentil seed losses reach even up to 55% [32]. This situation justifies the search for ways of limiting the phenomenon. There are reports on work on reducing pod cracking and lentil seed losses [43]. As botanically both siliques and lentil pods are classified as cracking dry fruits, measures aimed at improving agricultural techniques and harvesting technology may be used to limit the scope of the problem. One of the methods can be the application of preparations reducing pod cracking. Under the Polish conditions the yield of lentil is 1.0-1.2 t ha^{-1} [13]. In experimental conditions Dziamba and Linkiewicz [11] obtained an average seed crop yield of 1.5 t ha^{-1}, covering an extremely broad range of values from 0.13 t ha^{-1} to 3,43 t ha^{-1}. Lentil can be sown both in monoculture and – in view of its tendency to lodging – together with support plants. Błażej and Błażej [3] observed a lowering of the yield of lentil seeds in a mixed culture with oat, by an average of 0.5 t per hectare. In a pure culture they obtained yields of 1.8 t ha^{-1}. Apart from the dietary values for human nutrition, lentil is also used as green mass for animal fodder as its nutritional value is close to that of vetch. Successful attempts are made at breeding forms of lentil suitable for biomass with simultaneous application in combating soil erosion in the Middle East [52].

Proteins from leguminous plants, including lentil, due to their high nutritional value, may substitute – or largely complement – animal proteins in human diet, and that is the fundamental objective of growing lentil.

1.2. Botanical features

Consumption lentil – *Lens culinaris* Medik. – is one of five species of the genus *Lens* Mill. (lentil). The Polish literature does not discuss the multiplicity of lentil species, instead naming subspecies and botanical varieties. And thus the term "lentil" is understood to cover the species of consumable lentil (*Lens culinaris* Medik., syn.: *Lens esculenta* Moench., *Lens sativa* Hell., *Ervum lens* L.). Regional synonyms in Polish are "sacówka" and „sokówka", while in English they are all covered by the broad term "Lentil". The botanical varieties described differ from one another in the duration of their period of vegetation, plant height, weight of 1000 seeds, and in the appearance of the seeds:

- *Ssp. esculenta, var. vulgaris* with yellow-green seeds; *f. punktata* owith yellow seeds with a number of black spots,
- *Ssp. esculenta, var. macrosperma* with large yellow-green seeds or small brown veined seeds; *f. erytrosperma* (red-brown seeds, small); *f. nigra* (black seeds, very small) [50].

Seed size and plant height are the criteria for the identification of two subspecies: small-seed lentil *ssp. microsperma* Baumg. – weight of 1000 seeds below 30 g, plant height 15-30 cm, and large-seed lentil ssp. *macrosperma* Baumg. – average weight of 1000 of 60 g, plants with a height of 40-75 cm. Lentil is an annual plant (biennial forms are also known), with a vegetation period lasting from 60 days for very early varieties to 140 days for late varieties. It has a weakly developed root system, characteristic for vetch plants, located in soil layer down to 40 cm. The plant is characterized by a weak growth of green mass. Its stems are raised, branching from the base, reaching heights of 15-50 cm. Stems are rectangular in cross section, with a groove, flexible and pubescent. The plants have varied degrees of branching, as a rule of the 1^{st} or 2^{nd} order. Leaves with small stipules, geminately pinnated, with 3-7 pairs of narrow elliptical pinnules, upper ones frequently with a tip tendril. The inflorescence is a short raceme located in the angle of leaves. Small flowers, up to 8 mm long, blue, white, pink, or purple, grouped in a cluster. Ten stamens (9 accreted, 1 free), one pistil. Lentil is an autogamous plant. It blooms from the bottom upwards. Flowers formed in the final part of the vegetation period do not set pods, and those pods that may be set do not mature. The first branching blooms for a period of a dozen days or so, and the blooming period of lentil lasts from one half to two thirds of the whole vegetation period. The fruits are pendent pods containing 1-3 seeds (most often 2), trapezoid in shape, up to 20 mm long. A lentil pod is a single-chamber fruit formed of a single carpel. It has two raphes, ventral and dorsal, which crack dividing the pod into two shells and releasing the seeds. Lentil seeds are round and lens-shaped, uniformly coloured or spotted, brown or of another colour, and smooth [15,16,45]. The weight of 1000 seeds varies extensively for different forms and populations of lentil, and in the experiments by Dziamba *et al*. [10] fell within the range from 18 to 58 g.

The Polish cultivars differ from the initial forms – they are taller (40-60 cm) and their leaves are composed of a large number of pinnules (more than 11). A characteristic feature of the Tina cultivar is the green colouring of its cotyledon, and its weight of 1000 seeds is about 50 g, as opposed to the yellow colouring of the cotyledon and weight of 1000 seeds of 40 g in the case of the Anita cultivar. Work on breeding new lentil cultivars through crossbreeding is difficult and labour consuming, due to the specific character of lentil blooming and of fertilizing the small flowers, and therefore the utilization of selection and of mutagenesis plays an important role in lentil breeding programs [14,18,20].

1.3. Chemical properties

A valuable features of lentil is its high content of proteins in seeds. According to Norton *et al*. [24] lentil seeds contain 23.8% of total protein, according to Bobrecka-Jamro, Szpunar-Krok [4] – 29.7%, and according to Piróg *et al*. [26] – 30.4%. The protein is characterized by good digestibility, contains essential amino acids, and can complement cereal proteins in human diet. The amino acid composition of lentil, as with other leguminous plants, is characterized by a high content of lysine. Amino acids limiting the quality of lentil proteins are methionine and cystine, like in the case of pea seeds [28]. Lentil seeds contain approximately 44% of starch and from 0.77 to 1.74% of fat, and such mineral components as potassium, phosphor, magnesium and calcium [27,49]. According to Jasińska and Kotecki [14], the nutritional value of lentil seed is evidenced by its content of total protein at 32% of dry mass, raw fat of 1.5%, fibre of 4.8%, ash content of 3.7%, and 58.0% of nitrogen-free extractable substances. The content of oligosaccharides does not exceed 5%, and that of monosaccharides 3%. The quality of the seed is also determined by the content of anti-nutrients. These include trypsin inhibitors, and their occurrence in the seeds of leguminous plants restricts the utilization of proteins. Compared to soybean or pea, their content in lentil seeds is several times lower [29]. Beside beans and pea, lentil has a low value of so-called glycemic index, which allows it to be included in the diet for diabetics [6]. Results of analyses indicate, for both plant species, a high content of bio-elements such as iron, zinc, copper, manganese, molybdenum and selenium (Tab. 1). According to Bhatty [2], Chorąży [7], Dębski and Dębska [9], Piróg [28] and Lampart-Szczapa [17], the chemical properties and high nutritional and sensory values characterizing lentil caused that it has been "rediscovered" by dieticians and nutritionists. As a result, the plant has been accepted as highly valuable so-called "safe food".

Table 1. The content of mineral ingredients of lentil seed (M. Milczak *et al.*) [50]

Ingredient	Unit	
K	g kg^{-1}	10.80
P	g kg^{-1}	5.20
Ca	g kg^{-1}	1.00
Mg	g kg^{-1}	1.40
Na	g kg^{-1}	0.13
Fe	mg kg^{-1}	50.20
Zn	mg kg^{-1}	60.00
Al	mg kg^{-1}	5.78
Mn	mg kg^{-1}	6.26
Mo	mg kg^{-1}	6.92
Cu	mg kg^{-1}	5.40
Se	mg kg^{-1}	1.28
Li	mg kg^{-1}	0.68
B	mg kg^{-1}	2.88
Ba	mg kg^{-1}	0.20
Cr	mg kg^{-1}	0.24
Ni	mg kg^{-1}	0.49
Ti	mg kg^{-1}	0.15
V	mg kg^{-1}	0.36
Sr	mg kg^{-1}	1.19
As, Be, Cd, Hg, Pb	mg kg^{-1}	< 0.10

1.4. Physical properties

The first studies on the physical properties of lentil seeds in Poland were conducted by Szot *et al*. [38,40,41,42]. They determined the geometric features – thickness of width (describing them with normal distributions), the weight of one thousand seeds, bulk density and porosity, angles of repose and of slide, the resistance of individual seeds to static loads, and performed stress relaxation of seeds in bulk. The authors determined also the effect of moisture on the variability of those properties, and described it by means of linear or curvilinear regression. An interesting aspect of the studies was a comparison of the variability of physical properties of lentil seeds of two varieties – one Polish and one Canadian – which showed significant differences for numerous features of the seeds [37]. A strong effect of moisture on the physical properties of seeds was also confirmed by studies conducted on lentil (*cv*. Sultani) in Turkey, where interest in lentil production is strong [5].

This publication constitutes a summary of agrophysical studies on lentil performed so far.

2. OBJECTIVE OF STUDIES

The objective of the studies was to acquire knowledge on and to characterize the agrophysical properties of lentil in the aspect of obtaining lentil seeds of high quality. Knowledge of those properties is closely related with correct programming of the processes of harvesting, cleaning, drying, transport, storage, and also processing of lentil seed. It is, therefore, related with the quality of both the raw material and the final products. Two Polish registered lentil cultivars – Anita and Tina – were adopted as the experimental material. The assumed stage targets of the studies were the characterization of the biometric features of the plants and spontaneous seed shedding, and the determination of:

- the limiting effect of various preparations on pod cracking,
- the effect of moisture on the variability of geometric features of seeds,
- the effect of moisture on the variability of porosity, density, and angles of repose and of slide of seed in bulk,
- the effect of moisture on the variability of mechanical properties of individual seeds,
- the effect of moisture on the variability of mechanical properties of seed in bulk.

The relationships obtained provided the basis for defining those parameters responsible for the physical quality of the seed.

3. MATERIAL AND METHODS

3.1. Experimental material

Lentil seed for sowing material originated from the company „Spójnia"-Hodowla i Nasiennictwo Ogrodnicze Spółka z o.o. in Nochów, at whose grounds the creative breeding of the Tina and Anita lentil cultivars had been conducted. The sowing material obtained for the purpose of determination of the basic physical properties and their variability under the effect of moisture was subjected to tests in accordance with methods developed at the Institute of Agrophysics, Polish Academy of Sciences (PAS) in Lublin [35,36,44]. The seeds were wetted to the level of moisture content of 24% and measurements were taken in the course of natural moisture decrease at 1.5% increments, until reaching values corresponding to air-dry seeds. After analysis of the results, five levels of moisture content were adopted for the main study, at 3% moisture increments (9, 12, 15, 18, 21%).

Plants constituting the experimental material originated from our own experiment. The first field experiment with two lentil cultivars – Tina and Anita – was set up, in three replications, in the spring of 2000 at the Institute of Agrophysics, PAS.

The forecrop was wheat after potato. Full post-harvest tillage was applied, as well as pre-winter ploughing in the fall. Spring tillage included the application of spring harrow with string roller. 40 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1} were applied in the fall, and 20 kg N ha^{-1} before sowing in spring. Plot area was 45 m^2 (15 x 3m), with row spacing of 25 cm. Taking into account the germination capacity of the seeds, the sowing rates applied were 160 seeds m^{-2} for Tina and 190 seeds m^{-2} for Anita (recommended sowing rates are 100 kg ha^{-1} for Tina and 120 kg ha^{-1} for Anita). Sowing was performed using a single-row seed barrow. Seed dressing used was Funaben with Oftanol. Sowing was made on 15th April. Following the sowing, chemical weed control was applied by spraying the soil with Azogard (3 kg ha^{-1}) with Dual (1,5 l ha^{-1}). Later on, weeding was performed by hand. Systematic monitoring of the experiment was maintained, supplemented with photographic documentation. First plant emergence (approx. 20%) was observed on 24th April, and two weeks after the emergence the plants had two 1st order branches each, with a length of 4-6 cm. During the second decade of June the beginning of blooming occurred for Anita; Tina was still before its blooming phase. The first green pods were formed on Anita plants at the end of June, followed by Tina 7-10 days later. Ripening of first (bottom) pods occurred in the third decade of July, and at the end of July the plants were harvested by hand. Harvesting the lentil was started when the pods were brown and the seeds in them hard.

The above procedure was also followed for the field experiment in 2001. The relatively slight changes concerned the time of tillage and chemical treatments application, ripening, and sample taking, and were related to the differences in the weather between the two years.

The course of plant vegetation in the plots is presented in photos 1-6.

Photo 1. Emergence of lentil plants

Photo 2. Plants prior to blooming

Photo 3. Full blooming

Photo 4. Green pod phase

Photo 5. Full ripeness

Photo 6. Lentil plants of Anita and Tina varieties with visible differentiation in pod mounting height

3.1.1. Scope of the studies

The studies were conducted according to an adopted schedule, and the full scope of the work is presented in the form of a schematic (fig. 1 and 1a).

3.2.Methods

3.2.1. Biometric features of plants and seed yield

Measurements of the biometric features of the plants – for purposes of their characterization – were taken in the phase of full ripeness, prior to the harvest. Plants were sampled at random, from designated areas of 3 x 1 m^2 for each of the cultivars. For direct measurements 50 plants were taken per cultivar in each of the two years of experiment. A special measurement table with fixed graduated rulers was used to determine the following:

- plant height (cm),
- number of branches (pcs),
- height of the lowest pod (cm),
- number of pods on plant (pcs).

Additional determinations concerned the moisture of pods and seeds from the plants taken for the measurements.

Independently from the measurements, threshing by hand was used to determine the yield of seeds per 1 m^2, applying the principle of 3 replications from each plot for a given cultivar, as well as the average yield from 1 plant (50 replications). Photograph 7 presents seeds of the Tina and Anita cultivars.

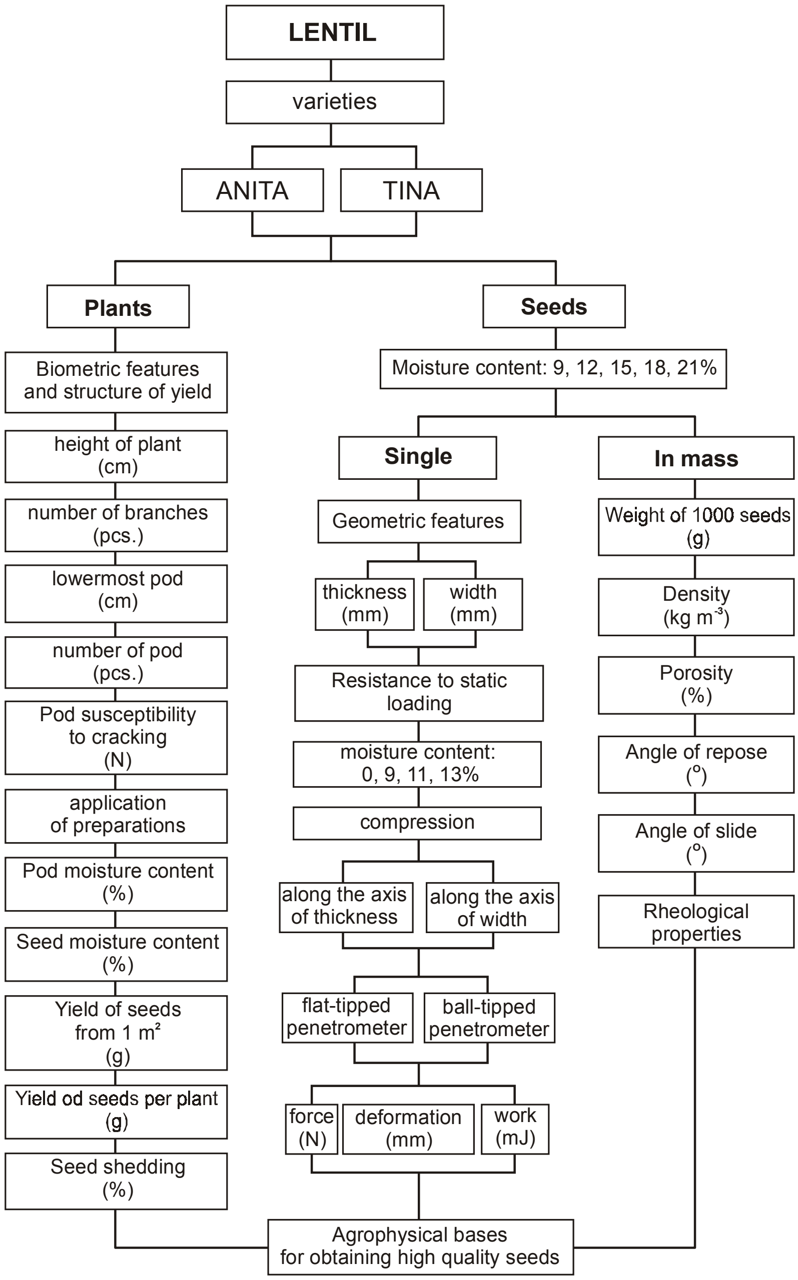

Fig. 1. Block diagram of the scope of studies of agrophysical properties of lentil

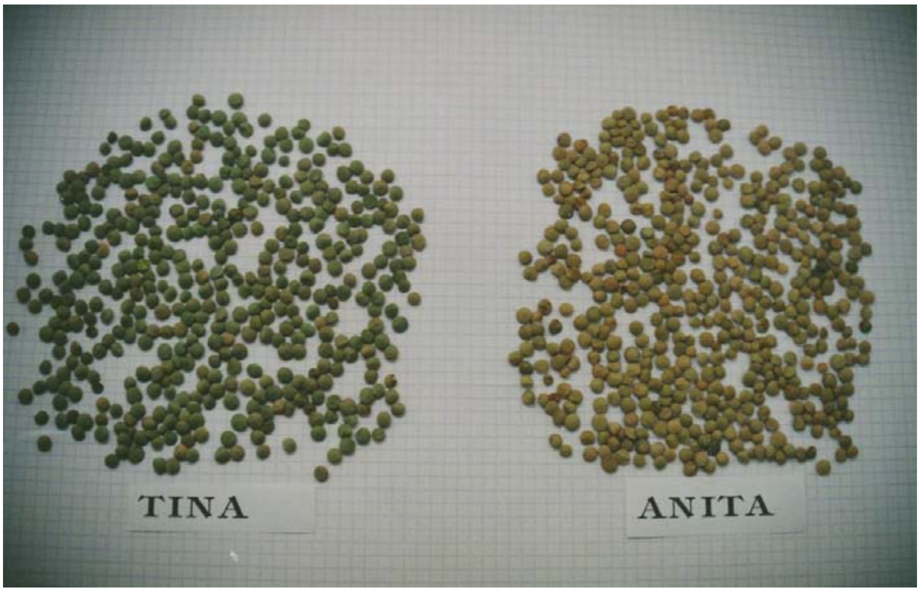

Photo 7. Lentil seeds of the Tina and Anita varieties

3.2.2. Spontaneous shedding of seeds

Estimation of spontaneous shedding of seeds was made on the experimental plots. For this purpose, metal frames enclosing areas of 1 m^2 (1 x 1 m) were placed at random on the plots and two days were selected to count seeds shed during the ripening of the plants. Six replications were applied for each cultivar. After harvesting the plants, by hand, from those areas, the seed yield was determined and percentage share of shed seeds was calculated. Only spontaneous shedding of seeds during plant ripening was determined. Due to the very low resistance of the pods to cracking further seed shedding takes place during the harvest by hand, and in combine harvesting seed losses due to pod cracking may even exceed 20% of the seed crop.

3.2.3. Application of preparations

In order to determine the limiting effect of preparations on pod cracking, an experiment was conducted on isolated plots of lentil, 8 m^2 in area, involving spraying the plants with water solutions of suitable preparations.

The following preparations were used in the experiment:

Spodnam DC – active component: di-p-menthene [cyclohexane polymer, 1-methyl-4-(1-methyl-ethyl)]. Little harmful for humans but harmful for fish and other aquatic organisms (class II). It is a growth regulator, forming a semi-permeable film retarding water absorption from outside of the plant. It has some inhibitory effect on silique and pod cracking and seed shedding. Studies on rape pod cracking showed an improvement of pod resistance to cracking by 20% [43]. Applied at the dose of 1.5 dm^3 ha^{-1} (per manufacturer recommendations). Spraying applied about two weeks before the harvest (when lower pods on lentil plants began browning).

Reglone – one of the dipyridyl herbicides. Chemically it is diquat dibromide (N dibromide N'-ethylen-2, 2'-dipyridyl). Used on a large scale for plant desiccation and defoliation, as a total herbicide, and in plant production primarily for equalization of ripening at the dose of 2.0 dm^3 ha^{-1} (per manufacturer recommendations). Spraying applied when lower pods were brown and middle pods began browning (4-5 days before planned harvest).

Starch - polysaccharide constituting reserve material for plants, accumulated in leaves, seeds, fruits, roots and tubers. Commonly available and ecologically friendly, that is easily decomposing. In the experiment applied as an impregnating-bonding agent. Three types of starch were selected, differing in granule size, as that feature has a decisive effect on the viscosity of the water solutions obtained. Spraying applied during pod browning. The following starch types were used:

1. Potato starch, characterized by the largest starch granules. Granule diameter about 100 µm. This starch forms meals of high viscosity,
2. Wheat starch, containing both small and large granules [23],
3. Amaranthus starch (from the species *Amaranthus cruentus*), with exceptionally small granules of 1-3 µm [30], and according to Fornal and Szot [12] the granule diameter does not exceed 2µm.

The starch preparations were first modified through dissolution in water with a temperature of 90°C. From the solutions of wheat and amaranthus starches sediment was removed by filtering. For lentil plant spraying an 0.75% water solution of potato starch and 1% water solutions of the other starches were used. Spraying was performed with a Kwazar hand-operated pressure spraying machine (working pressure of 0.35 MPa).

In the individual plots of the experiment each of the preparations was applied separately; in the control plot no treatment aimed at modifying the properties of lentil pods was applied. During the phase of full ripeness, pod samples were taken for the assessment of their susceptibility to cracking in accordance with a method developed earlier. An Instron strength tester was used to determine the parameters at which lentil pods treated with the preparations cracked in a tensile test [39].

3.2.4. Pod susceptibility to cracking

Lentil pods for the strength tests were taken during the phase of full ripeness. Sample preparation consisted in pulling plants from the soil by hand successively in the order they grew in rows in the particular combinations of the experiment. This was necessary due to the "intertwining" of plants in a row. Next, also by hand, holding pods by their stems, all the pods were pulled from the plants. That special care in collecting the material resulted from the very low values of force that caused pod cracking. After discarding pods that were poorly developed, unripe or damaged, samples of 120 pods per cultivar were set apart for the measurements. The measurements were made on pods with moisture of 11%.

The developed method for the estimation of lentil pod susceptibility to cracking consists in the determination of the maximum force and work required to open a pod, i.e. to separate the pod shells. Profiled pull wires, 0.25 mm in diameter and 50 mm long, made of brass wire, were attached with a special adhesive to both sides of individual pods (photos 8, 9). Then the pull wires were fixed in the grips of the Instron strength tester and tension was applied until the moment of pod opening (cracking along the pod seams). A schematic of the tensile test is presented in figure 2. The graphs obtained permitted the determination of the force and energy causing pod cracking. A typical process of lentil pod cracking is presented in figure 3.

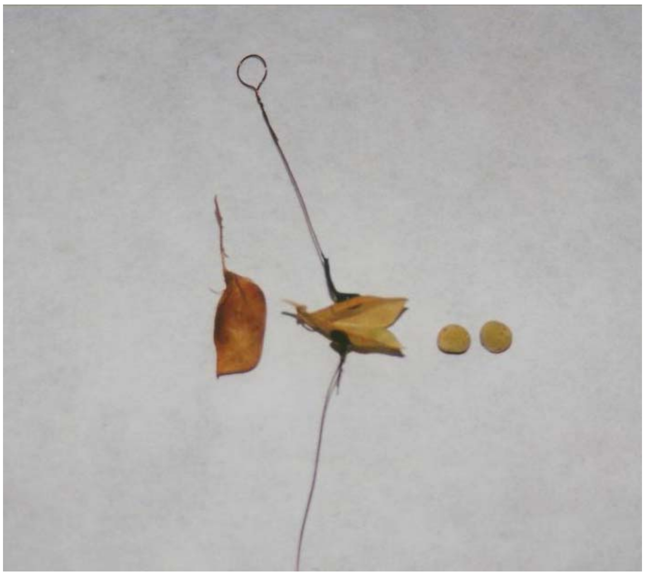

Photo 8. Lentil pod prior to preparation for measurements and pod open after the measurement

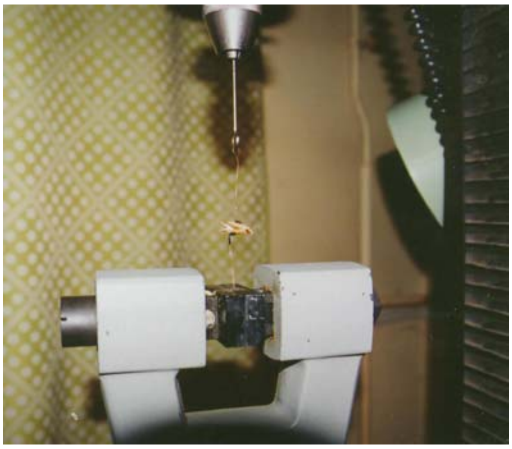

Photo 9. Measurement of pod resistance to cracking

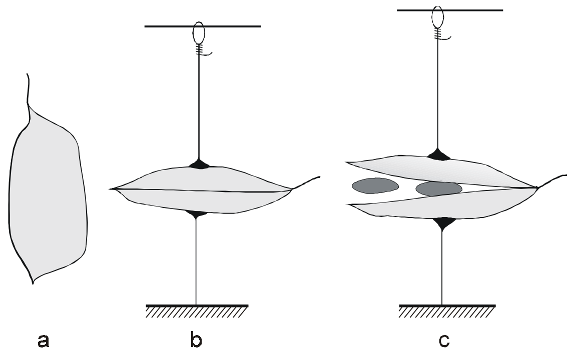

Fig. 2. Lentil pod (a), fixing method (b), pod cracked after tensile test (c)

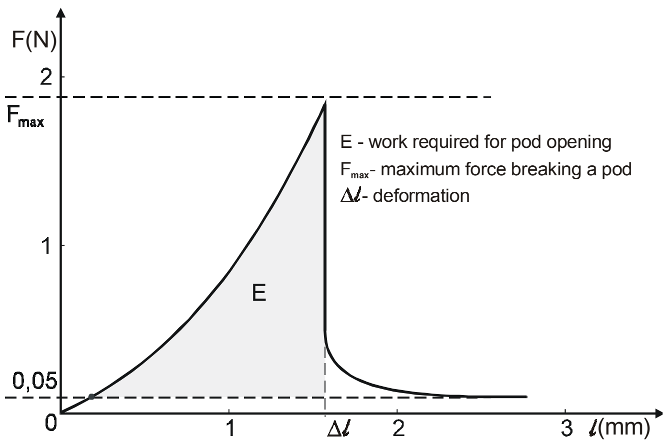

Fig 3. Typical run of the process of lentil pod cracking

3.2.5. Moisture content of the material

Measurements of the physical properties of lentil seeds within the scope of the main study were conducted at 5 levels of seed moisture content, and namely: 9, 12, 15, 18, 21% (±0.2%). Only in measurements of the physical properties of individual seeds the moisture content levels adopted were 0, 9, 11 and 13%, as it had been found earlier that individual seeds of lentil with higher moisture were subject to plastic deformation. Depending on the bulk moisture content of seeds, determined with the drier method on electronic drier-scales type WPE 30 S, samples of lentil seed were dried, spread on a laboratory table at ambient temperature, or wetted in accordance with a method developed at the Institute of Agrophysics, PAS [44]. The method, with frequent moisture content checks on the drier-scales, permitted the obtaining of material with required moisture content with maximum deviation of ±0.2%. Seed in bulk prepared in this way was used to isolate samples for the determination of the physical properties of two lentil cultivars.

3.2.6. Geometric features of individual seeds

Lentil seeds are specific in terms of their shape. They are almost the shape of a typical lens, its surface systematically rising from the edge towards the centre. Therefore, one can measure the thickness and the width of the seed whose projection on the horizontal plane form almost a perfect circle. The measurements, therefore, comprised the determination of the thickness and the width (diameter) of the seeds, by means of a specially adapted dial gauge, with an accuracy of 0.01 mm (photo 10). Material with a moisture content of 9% was used to make measurements of seed thickness and width, in 300 replications for each feature. The amount of data obtained permitted the full range of values to be covered for the features of each of the cultivars, as well as the determination of the distributions of those features based on the frequency of occurrence of particular fractions of thickness or width.

For the other levels of seed moisture content, measurements of the features were made in 60 replications per feature, to obtain mean values that would provide numerical characterization of changes in seed thickness and width with changing seed moisture content.

Material with the same levels of moisture content was used for further studies on the physical properties, including measurements of the mechanical strength of both individual seeds and of seed in bulk.

Photo 10. Meter for the determination of geometric features of seeds

3.2.7. Weight of 1000 seeds, porosity, density, angles of repose and slide of seeds in bulk

The weight of 1000 seeds was determined with the help of a seed counter type LN-S50A, after its adaptation for the size of lentil seeds. Three replications were made for each seed moisture content level. The seeds were weighed using an electronic balance, MEDICAT 160M, with an accuracy of 0.001 g.

Bulk porosity of the seeds was determined with the help of a pressure porometer (photo 11). The apparatus had been adapted for the determination of porosity of seed samples in heaped state in a cylinder of 100 cm^3 in volume. The readout of porosity, with an accuracy of 0.5%, is taken in a scale covering the range from 0 to 100%. In the determination of this feature, the rule of 10 replications for each combination of the experiment was applied.

The mass of 1 m^3 of seeds (bulk density) was determined with the help of a densimeter for cereal grain. The measurements were taken in accordance with the Polish Standard PN R-74007, with 4 replications for each level of seed moisture content.

The angles of repose and slide were measured with the help of a prototype apparatus comprising two chambers (photo 12). In the middle of the height of the apparatus, the chambers are divided with a shelf with a sliding shutter covering an aperture. After filling the upper chamber with seeds and opening the shutter, seeds fall freely to the lower chamber. Thanks to the transparent wall of the container, the angle of repose can be measured with the help of a protractor in the upper chamber, and the angle of slide – in the lower chamber. For each combination of the experiment 3 replications were made for both the parameters.

Photo 11. Porometer for the determination of seed mass porosity

Photo 12. Method for the measurement of angles of repose and slide

3.2.8. Mechanical properties of individual seeds

Studies of the mechanical properties of individual seeds were performed on seed with moisture content levels of 9, 11 and 13%. That range of moisture content resulted from preliminary tests which showed that lentil seeds with higher moisture content were subject to plastic deformation (curves of compression did not show characteristic points, e.g. so-called bioyield point). For comparative purposes, in 2000 an additional study was made on the mechanical properties of individual seeds with a moisture content of 0%. Preparation of such seeds consisted in prolonged (5 hours) drying of lentil in a laboratory drier with forced ventilation of the drier chamber.

In the study on the mechanical parameters of individual lentil seeds a specially designed adapter was used, permitting the measurement of characteristic parameters to be made in two planes. It was a table permitting seeds to be compressed when positioned with the plane of cotyledon division parallel (cotyledon division plane vertical) and perpendicular (cotyledon division plane horizontal) to the direction of the compressive force application. Moreover, tests were performed with two types of penetrometers – ball-tipped and flat-tipped (photo 13 and 14). The measurements were made in 30 replications for each combination of the experiment – variety, moisture level and type of test. In the evaluation of sowing material, seeds were subjected only to compression between two plates.

Photo 13. Preparation of material and equipment for the study of the mechanical properties of lentil seeds

The study on the resistance of individual seeds to loading was performed on an INSTRON model 6022 strength tester equipped with the adapter and penetrometers suitable for particular tests. Analogue signals from the strength tester were sent to a computer where, by means of an analogue-digital converter, they were converted into digital signals that could be recorded in the computer in the form of compression curves. The recorded curves were then analysed and the values of parameters characterizing the resistance of seeds to external loads were determined. The curves were analysed with the help of specially developed software that permitted the determination of the compression curve flex point by plotting a tangent line. The values of force and strain in the point determined in that way were assumed to be the limit values for a given test – at that point the seed cover damage occurred. The value of force and corresponding strain at the point determined in that way are conventionally called elastic force and elastic strain. Simultaneously, the software integrated the graph, which permitted the determination of the value of work required to damage the seed. Therefore, five values were used for the description of the mechanical parameters of an individual lentil seed – maximum force, elastic strain corresponding to the maximum force, elastic force, elastic strain corresponding to the elastic force, and work required to damage the seed.

Photo 14. Single seed compression in the vertical plane

3.2.9. Mechanical properties of seed in bulk

To determine the mechanical parameters of lentil seed in bulk the stress relaxation test was performed with the help of an Instron model 6022 apparatus. Seed sample was placed in a steel cylinder with a diameter of 50 mm and loaded with a piston with slide fit to the cylinder (Photos 15, 16). The height of the seed column was 100 mm, and the relative deformation of the seed column was equal to 10%. After the assumed sample deformation had been effected, the measurements were taken. At predetermined time intervals (every 20 seconds) the value of force was recorded (seed column response to the load). Simultaneously, the relaxation curve was plotted in the strain-time system of coordinates.

Photo 15. Seeds prepared for the stress relaxation test

Photo 16. Stress relaxation test – cylinder placed in the „Instron" strength tester

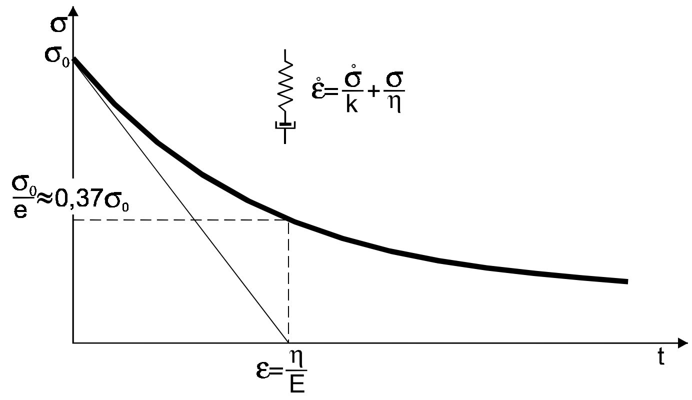

Fig. 4. Schematic of relaxation curve in the strain-time system and its interpretation with the Maxwell model.

The results of the test were interpreted with the Maxwell model in which the strain-time relation is described by the equation:

$$F(t) = \sum_{i=1}^{n} A_i e^{-\alpha_i t}$$

where: F(t) – change in the value of force [N], t – time [s], A – model coefficient [N], α – model coefficient.

For the purpose the relaxation curve was read into the computer in digital form, and then the parameters of the equation that provided the best approximation of the curve were determined numerically. Then the parameters were substituted in the equations of the Maxwell model and its coefficient values were calculated.

4. RESULTS

4.1. Characterization of sowing material

For air-dry seeds (~9% of moisture) the mean thickness of seeds of the Tina cultivar was 2.53 mm, and of those of the Anita cultivar – 2.48 mm. Seed width was 5.58 and 5.79 mm, respectively. Tina had somewhat thicker seeds, and those of Anita were wider. A suitable number of replications in the measurements permitted the description of those features by means of normal distributions (figure 5, 6) which confirm the existence of differences between the cultivars. The dimension of seed thickness formed ranges from 1.75 mm to 3.07 mm (Tina) and from 1.90 mm to 3.40 mm (Anita), while that of width varied within ranges of 4.73 – 6.80 mm (Tina) and 4.60 – 6.80 mm (Anita).

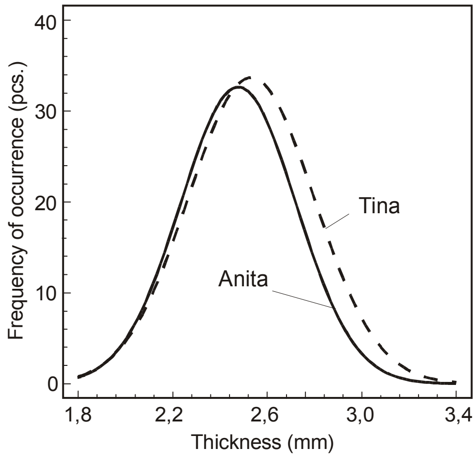

Fig. 5. Seed thickness distribution for the Tina and Anita lentil varieties

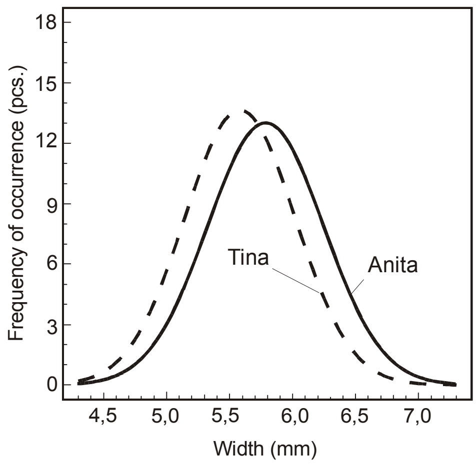

Fig. 6. Seed width distribution for the Tina and Anita lentil varieties

The weight of 1000 air-dry seeds of the Tina cultivar was 49.36 g, and of those of the Anita cultivar – 48.05 g. Those values increased with increasing seed moisture content, and the character of the changes was described with regression lines (figure 7). Those permitted the reading of predicted values of one parameter if the value of the other was known. Bulk density of the seeds, on the other hand, increased with decreasing seed moisture content (figure 8), reaching the value of 806 kg m^{-3} for dry seeds of Tiny and 795 kg m^{-3} for Anita. The character of the changes, however, was somewhat different for the two cultivars. The relation between Tina seed bulk density and moisture was described by the closest fitted curve of regression, while that for the Anita cultivar was characterized by linear regression. The lowest value of seed bulk density (at the highest moisture content) was convergent for both cultivars and oscillated around the value of 747 kg m^{-3}.

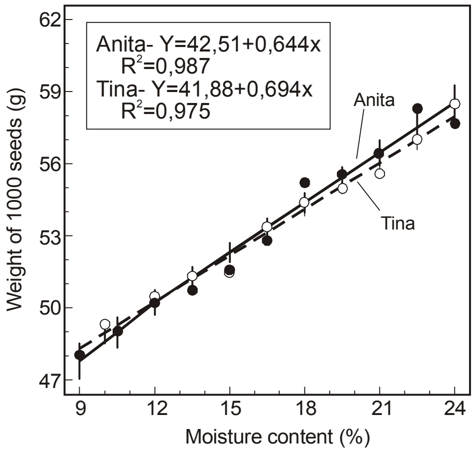

Fig. 7. Relationship between moisture and weight of 1000 seeds of Anita and Tina lentil varieties

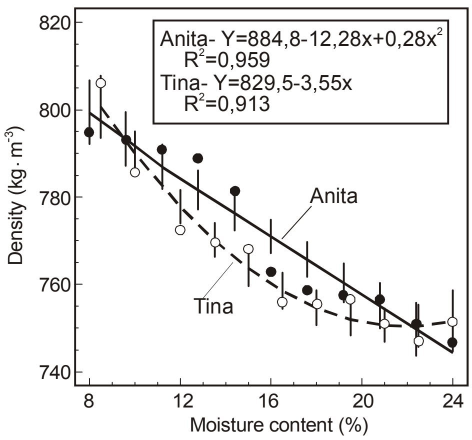

Fig. 8. Relationship between moisture and density of Anita and Tina lentil seeds

The angle of repose of lentil seed is lower than the angle of slide. For dry seed of the Tina cultivar the values of the angles are 23.0º and 27.5º, respectively, and those for Anita – 27.0º and 30.0º (table 2). With increasing moisture, there is a certain increase in the values of angles of repose and slide, but within the range of seed moisture content of 21-22.5% a decrease is observed in the values of the parameters. It is only at the highest seed moisture content (24%) that the angle of repose for Tina reaches the highest value of 32º, as does the angle of slide – 34º. At the same level of moisture content the seeds of Anita are characterized by the angle values of 31º and 32º, respectively. These variations in the values of the angles of repose and slide at high moisture levels can be explained by, unknown so far, physical or physicochemical changes on the surface of the seeds and the character of their contact with neighbouring seeds. Providing an explanation for these issues may prove valuable in the design of processes of internal transport, storage, and lentil seed processing technologies.

Table 2. Mean values of angles of repose and slide of TINA and ANITA lentil seeds at various levels of seed moisture.

Moisture (%)	Variety			
	TINA		ANITA	
	Angle of repose (°)	Angle of slip (°)	Angle of repose (°)	Angle of slip (°)
24.0	32.0	34.0	31.0	32.0
22.5	30.0	33.0	27.0	30.0
21.0	29.0	30.3	27.0	30.0
19.5	31.5	30.8	32.0	31.5
18.0	30.0	31.0	30.0	31.5
16.5	29.5	30.0	29.5	30.5
15.0	29.5	29.5	30.0	30.6
13.5	29.0	28.6	28.5	31.0
12.0	28.0	27.6	28.5	30.5
10.0	27.0	28.5	27.5	30.0
8.5	23.0	27.5	27.0	30.0

Lentil seed bulk porosity decreases with decreasing moisture, to the value of 45.3% for Tina and 44.0% for Anita. The highest values of porosity, at very high seed moisture content, exceed 47% for Tina and 46% for Anita. The relation of this parameter of lentil seed to moisture is not linear and was described by means of curves of regression for the two cultivars which differ from each other (figure 9). Knowledge of the characteristics of changes in lentil bulk density may be highly useful in the process of drying, as that property affects the flow of the drying medium through the seed layer and the level of resistance to the flow. Therefore, it is directly related to energy consumption and the duration of the process of seed drying.

The resistance of seeds to the effect of external forces is strictly related to the extent of mechanical damage to the seeds in the course of harvest, transport or other stages of post-harvest processing, and to the behaviour of the seeds during technological processes involved in the processing of the raw material. The resistance changes with varying moisture content of the seeds. Dry lentil seeds (8-14% of moisture) display elastic-brittle properties and tend to crack under the effect of applied force, which can be registered as damage to the seed structure. Seeds with higher moisture content assume visco-plastic properties and are subject to permanent deformation under the effect of increasing force. Tests showed that the destruction of the structure of a single dry lentil seed of the Tina cultivar required the application of an average force of 96 N, and the range of variability of that feature spanned values from 53.7 N to 135.7 N (tab. 3).

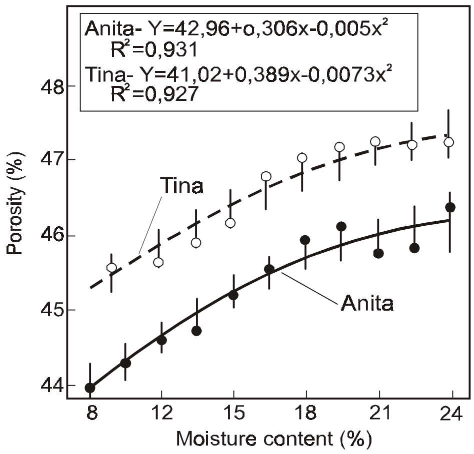

Fig. 9. Relationship between moisture and porosity of Anita and Tina lentil seed mass

Table 3. Mean values of force causing the destrucion of structure of dry lentil seeds (9%)

Parameters	Variety			
	TINA		ANITA	
	Force (N)	Deformation (mm)	Force (N)	Deformation (mm)
Mean values	96.0	0.28	125.5	0.50
Maximum	135.7	0.40	194.0	0.56
Minimum	53.7	0.21	67.2	0.16
Standard deviation	20.1	0.05	28.9	0.09
Coefficient of variability (%)	20.9	18.50	23.0	23.10

The Anita cultivar proved to be more resistant in this respect, as the average value of force causing the destruction of seed structure was 125.5 N, with a minimum of 67.2 N and a maximum of 194.0 N. To characterize the relation of the force crushing the seeds to the broad range of seed moisture content, a constant value of

0.25 mm was adopted as the limit value of seed deformation. The results obtained, described with regression curves (figure 10), clearly indicate a rapid drop in the value of the force with seed moisture content increase from 9 to 15%, followed by a certain stabilisation covering very low force values, i.e. below 10 N. The obtained characterization of lentil seeds to static loading indicates variability of the mechanical properties of the seeds, i.e. of features that determine the quality of the seed as a crop, as a consumption product, and as a raw material for the food industry.

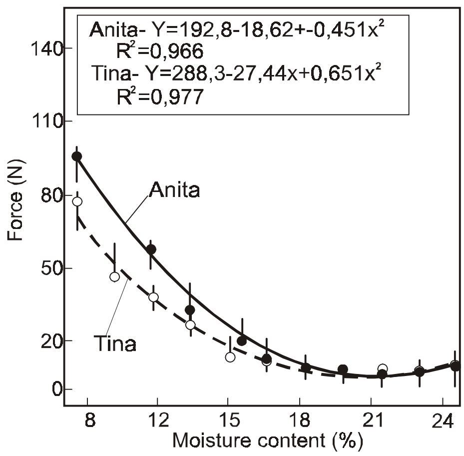

Fig. 10. Relationship between the force of compression of lentil seeds of the Tina (a) and Anita (b) varieties and the seed moisture at constant deformation of 0.25 mm

The study conducted on the fundamental physical properties of the sowing material, with the inclusion of the effect of moisture content, permitted the formulation of a realistic scope of the main study and at the same time provided knowledge on the variability of the physical properties of lentil seed. The results obtained allowed suitable preparation of measurement tools and apparatus to be used for studies on material obtained from our own experiments.

4.2. Characterization of biometric features of plants and of seed crop

In the year 2000, spring drought caused that a part of the seeds did not germinate after sowing and, as a result, the remaining plants, having more space available, were characterized by a somewhat different profile than in 2001, when there were no disturbances in the weather conditions.

The values of the biometric features of lentil plants are presented in tables 4 and 5 which, after analysis of variance, apart from the mean, maximum and minimum values give also the coefficient of variation *W*.

The average height of plants the Anita cultivar in the year 2000 was 43.2 cm with a coefficient of variation of 14.5%, and in the following year it was 49.6 cm with *W* = 12%. Therefore, the cultivar responded to the differentiated weather conditions and in the former of the two years yielded notably lower plants, as opposed to the Tina cultivar for which the values of plants height in both the years were hardly varied and in this particular respect Tina proved to be a much more stable cultivar. The coefficient of variation for Tina was similar in value to that for Anita.

Table 4. Values of biometric features of lentil plants and of yield of the ANITA variety.

Feature	Unit	2000 Year				2001 Year			
		Mean	Min	Max	Coefficient of variability (%)	Mean	Min	Max	Coefficient of variability (%)
Height of plant	cm	43.20	30	60	14.5	49.26	40	65	12.0
Number of branches	szt pcs	4.84	2	6	50.3	2.84	2	5	21.7
Lowermost pod	cm	14.86	7	26	27.4	23.34	6	32	21.4
Number of pods	szt pcs	39.42	10	98	49.2	31.98	12	54	34.1
Pod moisture content	%	11.0	–	–	–	13.4	–	–	–
Seed moisture content	%	9.8	–	–	–	11.2	–	–	–
Yield of seeds	g	106.1	–	–	–	152.3	–	–	–
Yield of seeds per plant	g	1.702	–	–	–	1.446	–	–	–
Seed shedding	%	3.30	–	–	–	2.49	–	–	–

The number of branches on the plants of both the cultivars was considerably greater in the first year of the study (Anita 4.84 pcs., Tina 4.48 pcs.) than in the following year – 2.84 and 2.18 branches, respectively. Analysis of variance showed a very strong variation of the feature in the year 2000 (*W* = 50.3% and *W* = 56.9%, respectively), while a year later the coefficient of variation comprised values only slightly exceeding the level of 20%.

The weather conditions of the year 2000 caused that the Anita cultivar set its pods low, as the average value of that feature was 14.86 cm above soil surface, while in the following year the corresponding value was 23.34 cm. In this respect Tina was much more stable and the values of the feature were 25.92 and 23,26 cm, respectively. Coefficients of variation for the two cultivars exceeded the level of 20%.

Table 5. Values of biometric features of lentil plants and of yield of the TINA variety.

Feature	Unit	2000 Year				2001 Year			
		Mean	Min	Max	Coefficient of variability (%)	Mean	Min	Max	Coefficient of variability (%)
Height of plant	cm	49.30	33	65	15.0	48.28	35	67	11.8
Number of branches	szt pcs	4.48	1	11	56.9	2.18	1	4	22.1
Lowermost pod	cm	25.92	17	44	21.6	23.26	12	41	24.8
Number of pods	szt pcs	40.54	7	94	47.2	35.42	10	86	41.7
Pod moisture content	%	12.1	–	–	–	19.4	–	–	–
Seed moisture content	%	11.8	–	–	–	18.4	–	–	–
Yield of seeds	g	122.1	–	–	–	141.3	–	–	–
Yield of seeds per plant	g	1.790	–	–	–	1.946	–	–	–
Seed shedding	%	2.11	–	–	–	2.58	–	–	–

It should be emphasized here that this particular feature of the plants is extremely important from the point of view of mechanized harvesting, as with pods located too low serious quantitative seed losses will occur due to the header of the combine cutting the plants above the lowermost pods. Minimum values of the feature for the Anita cultivar were as low as 6-7 cm, and this means that with plants leaning away from the vertical the pods would actually touch the ground. Better suited for mechanical harvesting is the Tina cultivar, for which even the minimum values were 12-17 cm.

The average number of pods on a plant of the Anita cultivar in the year 2000 was 39.42 pcs., and in 2001 – 31.98. Also Tina yielded more pods per plant in the first year of the experiment (40.54 pcs) as compared to the following vegetation season (35.42 pcs). For this feature, the coefficient of variation was much more varied for Anita ($W = 49.2$ and 34.1%) than for the much more stable in this respect Tina (47.2 and 41.7%).

In the year 2000 the moisture content of seeds of the Anita cultivar at the time of harvest was very low (9.8%), getting higher in the subsequent year (11.2%). Pod moisture in both the years was higher by about 2%. Seeds of the Tina cultivar at the time of harvest had higher moisture (11.8 and 18.4%), but with lower differences between the seeds and the pods (up to 1%).

Seed yield from 1 m^2 in the first year of the experiment was lower (Anita 106.1 g, Tina 122.1 g) than in the subsequent year (152.3 g and 141.3 g, respectively). Also in this case Tina proved to be the more stable crop. The mean seed yield per plant of the Tina cultivar for the two years of the experiment was higher than that of Anita, and all the values fell within the range from 1.446 g (Anita, 2001) to 1.946 g (Tina, 2001).

4.2.1. Spontaneous shedding of seeds

Both the cultivars shed seeds during ripening. Anita shed 3.45 g of seeds, which at seed yield from 1 m^2 at an average of 106 g meant that the mass of seeds shed constituted 3.30% of the yield. Seed yield of the Tina cultivar was 122 g from 1 m^2, and the amount of shed seeds was 2.55 g, which constituted a 2.11% loss of seed crop. The significantly greater amount of shed seeds in the case of the Anita cultivar indicates its higher susceptibility to pod cracking, related to the lower values of force and energy necessary to open the pods of that cultivar.

The results obtained in the year 2001 differentiated the two cultivars only to a small extent. Anita shed 3.75 g of seeds per 1 m^2 – with seed yield from 1 m^2 of 152 g this constituted 2.49% of the yield. Tina shed 3.55 g of seeds with a yield of 141 g of seeds from 1 m^2 (2.58% of the yield). Average seed losses due to spontaneous seed shedding, for the two years of the experiment, were 2.49% for the Anita cultivar and 2.34% for Tina. It should be mentioned here that during the periods of lentil plants ripening there were no particularly unfavourable weather conditions.

4.3. Effect of selected preparations on reduction of pod susceptibility to cracking

To acquire knowledge on the basic geometric features of pods, measurements were made of their length, thickness and width. Significant differences were found between the average values of geometric dimensions of pods of the cultivars under study. Average pod length of the Tina cultivar was 15.3 mm, and that of Anita 14.8 mm; width – 7.57 mm Tina and 7,84 mm Anita; thickness – 3.67 mm and 3.79 mm, respectively. Figure 11 presents the distributions of geometric dimensions of pods. Pods of the Anita cultivar were slightly thicker and wider, but much shorter, which gave them a bulging and squat appearance. Only a small variation was found in the geometric features of pods. The coefficients of variation fell within the range from 6.7% to 12.1%. The shape of Anita pods suggests a lower requirement for energy necessary for pod cracking in tensile test.

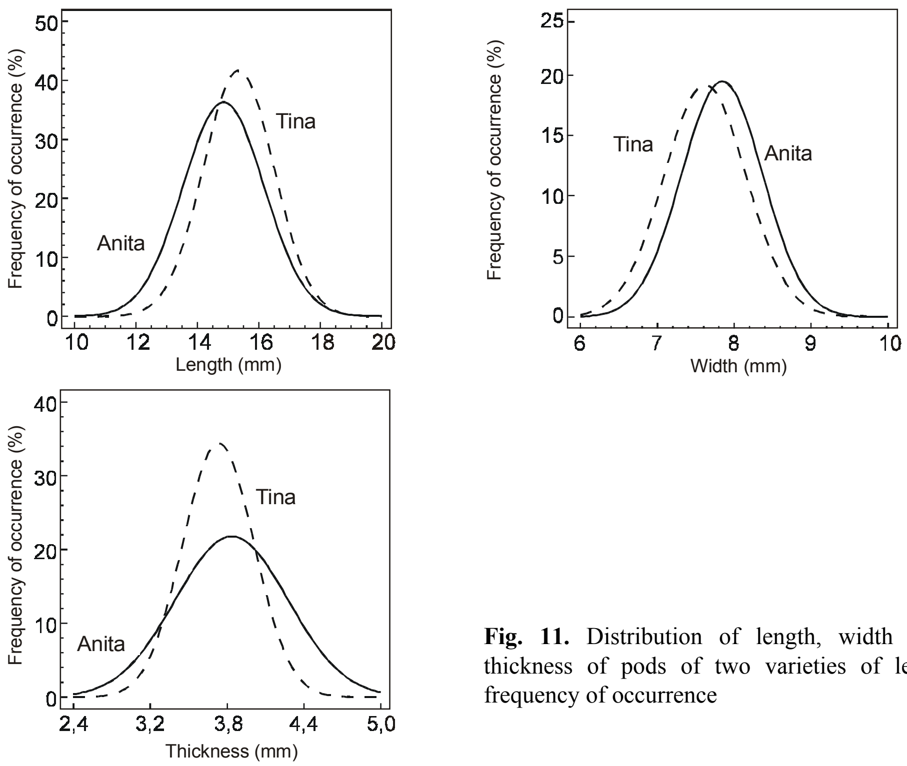

Fig. 11. Distribution of length, width and thickness of pods of two varieties of lentil frequency of occurrence

Cracking of pods of the lentil cultivars studied on the control material occurred at force values of 0.71 N for Anita and 0.89 N for Tina. The most effective in improving the resistance of pods to cracking were two preparations: Spodnam and potato starch (table 6). The value of force required to open lentil pods after the application of spraying with Spodnam increased by 0.32 N (36%) for the Tina cultivar, and by 0.12 N (17%) in the case of Anita as compared to the control material (figure 12). Potato starch also had a highly positive effect on pod cracking resistance, causing an increase in the force values by 0.22 N (25%) – for Tina, and by 0.26 N (37%) – for Anita. To a lesser extent and in a more varied manner was the pod resistance to cracking affected by amaranthus starch. A slight increase in force value was observed, of 0.06 N (7%) for Tina and 0.17 N (24%) for Anita. Wheat starch had no positive effect on that feature, causing a minimal increase in the force value measured – by 0.03 N in the case of Anita, while in the case of Tina even a decrease in the force value by 0.14 N. No effect was observed after the application of the Reglone preparation (change in the average force values by 0.03-0.05 N). Coefficients of variation for the preparations under study assumed similar values and oscillated from 41 to 60%.

Table 6. Mean values of force and energy causing lentil pods opening, and standard deviation and coefficient of variability *W* (2000-2001).

Preparation	Variety	Force (N)		Coefficient of variability (%)	Energy (mJ)		Coefficient of variability (%)
		Mean	Standard deviation		Mean	Standard deviation	
Potato starch	ANITA	0.97	0.54	56	0.70	0.75	107
	TINA	1.11	0.53	48	0.98	0.99	101
Wheat starch	ANITA	0.74	0.31	42	0.51	0.44	86
	TINA	0.75	0.32	42	0.70	0.89	127
Amaranthus starch	ANITA	0.88	0.37	41	0.73	0.79	108
	TINA	0.95	0.42	45	0.59	0.39	66
Spodnam	ANITA	0.83	0.42	51	0.63	0.39	62
	TINA	1.21	0.60	50	1.00	0.87	87
Reglone	ANITA	0.76	0.37	49	0.57	0.46	81
	TINA	0.92	0.53	58	0.70	0.78	112
Control	ANITA	0.71	0.42	59	0.61	0.46	75
	TINA	0.89	0.53	60	0.84	0.80	95

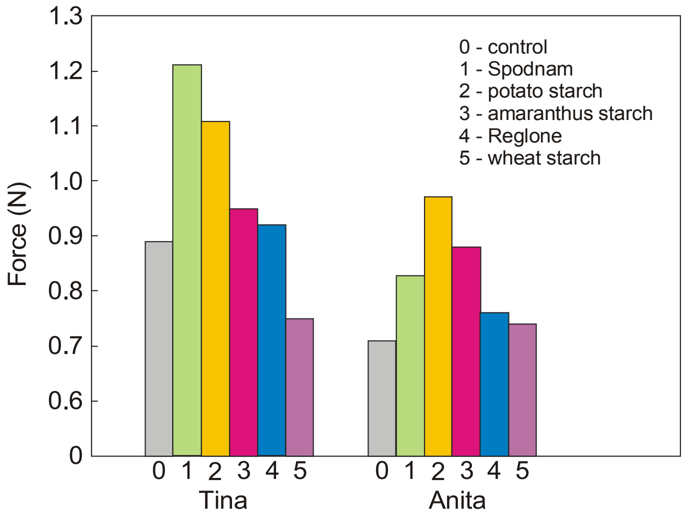

Fig. 12. Mean values of force causing pod opening, for two varieties of lentil

Determined in the study value of energy causing lentil pod opening in the control combination was 0.84 mJ for the Tina cultivar and 0.61 mJ for Anita (table 6, figure 13). The highest values of energy were obtained following the application of Spodnam – 1,00 mJ and potato starch – 0,98 mJ for the Tina cultivar. Therefore, the increase observed with reference to the control combinations was 16%. The response of Anita to the application of the preparations was similar to that of Tina only in the case of potato starch. After the application of what starch, amaranthus starch and Reglone the values of energy for both cultivars fluctuated without showing any clear tendencies – positive or negativ – and fell within the range of from 0.51 to 0.73 mJ. Characterizing the energy causing pod opening, a much higher variation of the parameter was observed as compared to the force values.

The coefficient of variation *W* was from 62% to 127%. The variation can be attributed to the features of lentil consisting in the uneven and extended in time ripening of pods and in the tendency of the plants to lodging. A part of ripe pods are located very close to the soil or even rest on its surface and are subject to daily wetting and drying, which affects their strength. Higher located pods are subject to such moisture oscillations to a much lesser degree and are at a different stage of ripening. Szot *et al.* [43] observed an unfavourable effect of alternating wetting and drying on the cracking resistance of rape pods which, due to their structure, are classified among cracking dry fruits, as the pods of lentil. The problem has also been noted by Weeks *et al.* [51] in their study on the mechanical properties of soybean pods.

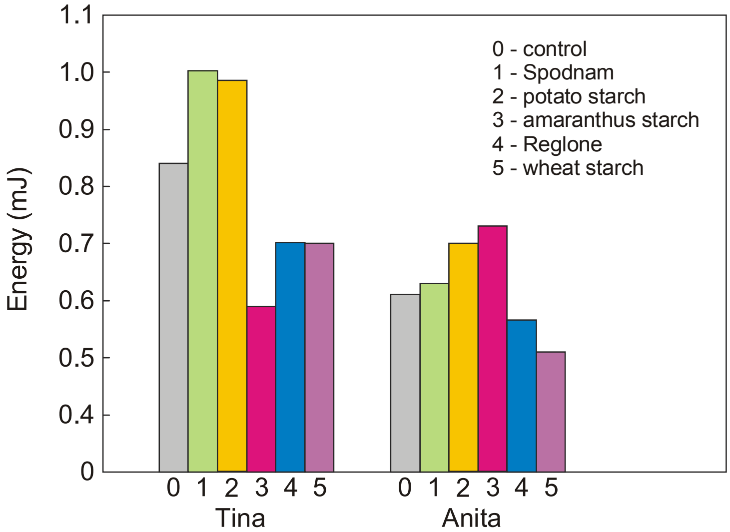

Fig. 13. Mean values of energy causing pod opening, for two varieties of lentil

4.4. Characterization of geometric features of seeds and the effect of moisture on their variation

In the year 2000 the average thickness of dry (9%) seeds of the Anita cultivar was 2.21 mm and in the following year – 2.41 mm, while the corresponding values for Tina were 2.35 and 2.47 mm, respectively (table 7, 8).

Table 7. Values of ANITA lentil seed thickness (in mm) in relation to moisture, and coefficients of variability *W*

Moisture (%)	2000 Year				2001 Year				Mean 2000-2001
	Mean	Min	Max	Coefficient of variability (%)	Mean	Min	Max	Coefficient of variability (%)	
9	2.21	1.60	2.96	8.39	2.41	1.87	2.96	7.14	2.31
12	2.34	1.62	2.90	9.01	2.46	1.96	2.85	7.28	2.40
15	2.38	1.85	3.02	9.50	2.52	2.15	2.87	6.49	2.45
18	2.42	1.93	2.99	9.26	2.63	2.10	2.97	2.69	2.52
21	2.47	1.82	3.05	9.21	2.62	2.33	2.90	5.45	2.54

Table 8. Values of TINA lentil seed thickness (in mm) in relation to moisture, and coefficients of variability *W*

Moisture (%)	2000 Year				2001 Year				Mean 2000-2001
	Mean	Min	Max	Coefficient of variability (%)	Mean	Min	Max	Coefficient of variability (%)	
9	2.35	1.79	2.95	7.69	2.47	1.77	2.99	8.91	2.41
12	2.66	2.26	3.30	9.92	2.51	1.95	2.86	7.41	2.58
15	2.51	2.03	3.07	9.12	2.61	2.05	2.92	8.10	2.57
18	2.58	1.49	3.18	10.04	2.61	2.15	2.75	3.79	2.59
21	2.65	2.10	3.28	9.36	2.55	2.25	2.80	4.88	2.60

Both the cultivars, therefore, bore somewhat thicker seeds in the second year. For a fuller characterization, on the basis of 600 measurements the feature was described by means of normal distribution concerned solely with seeds with the moisture content of 9% (figure 14). The distributions, as well as the tabulated data, indicate clearly that the Tina cultivar has thicker, more shapely seeds.

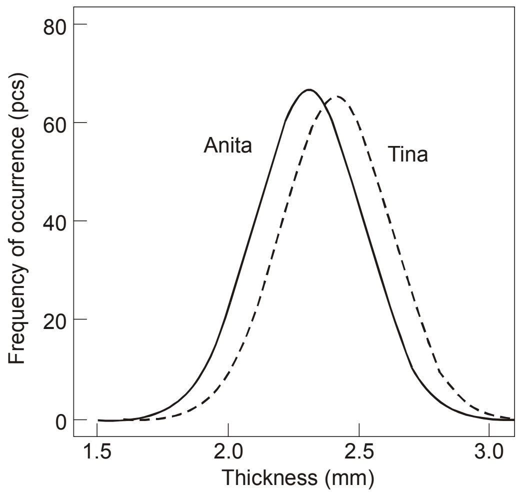

Fig. 14. Seed thickness distribution for the Anita and Tina lentil varieties

For the same moisture, the width of seeds of the Anita cultivar was 5.63 mm in the first year of the experiment and 5.72 mm in the second. The corresponding values for Tina seeds were 5.76 and 5.61 mm, respectively (table 9, 10). In this respect the two cultivars, both in the particular years and on the basis of two-year data, differ from each other only minimally and one can accept them to be nearly identical (figure 15).

Table 9. Values of ANITA lentil seed width (in mm) in relation to moisture, and coefficients of variability *W*

Moisture (%)	2000 Year				2001 Year				Mean 2000-2001
	Mean	Min	Max	Coefficient of variability (%)	Mean	Min	Max	Coefficient of variability (%)	
9	5.63	4.53	6.40	6.54	5.72	4.24	6.75	5.81	5.68
12	5.79	4.90	6.78	6.24	5.80	5.20	6.63	5.03	5.79
15	5.75	5.08	6.23	4.89	5.86	5.22	6.41	5.04	5.80
18	5.77	4.42	6.50	7.42	5.95	5.17	6.87	5.96	5.86
21	5.84	4.70	6.44	5.79	5.98	5.10	6.72	5.64	5.91

Table 10. Values of TINA lentil seed width (in mm) in relation to moisture, and coefficients of variability *W*

Moisture (%)	2000 Year				2001 Year				Mean 2000-2001
	Mean	Min	Max	Coefficient of variability (%)	Mean	Min	Max	Coefficient of variability (%)	
9	5.76	5.11	6.88	5.29	5.61	4.46	6.45	6.64	5.68
12	5.81	5.15	6.70	6.00	5.64	4.92	6.27	5.96	5.72
15	5.81	5.19	7.02	6.53	5.77	5.00	6.62	6.93	5.79
18	5.87	5.15	6.55	5.64	5.76	5.33	6.67	5.01	5.81
21	6.08	5.44	6.99	6.28	5.93	5.46	6.56	4.63	6.00

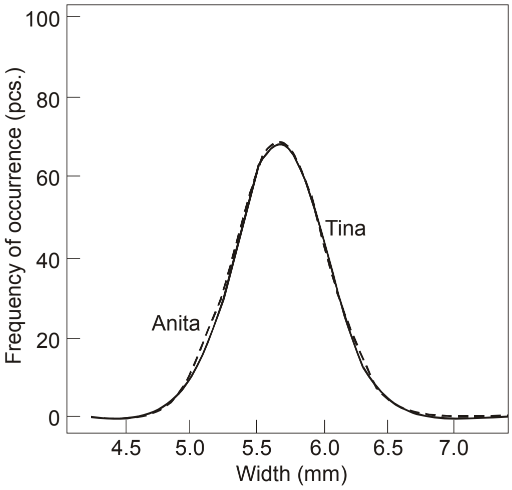

Fig. 15. Seed width (diameter) distribution for the Anita and Tina lentil varieties

Increasing moisture content of seeds caused their swelling. Seed thickness of the Anita cultivar increased systematically up to the moisture content of 21%, but the absolute values of the feature increased by only slightly more than 0.2 mm. The response of Tina seeds to moisture was similar, the difference being that in the first year the increase in seed thickness reached 0.3 mm.

Seed width also increased with increasing moisture, and differences between extreme values were similar to those observed in the assessment of seed thickness (Anita 0.2 mm; Tina 0.3 mm). The relationships determined are presented in figures 16, 17.

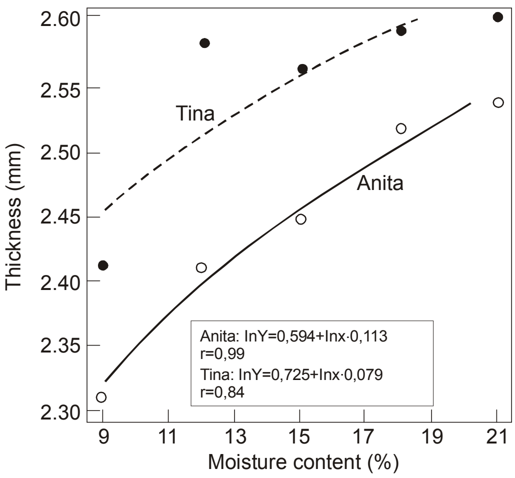

Fig. 16. Relationship between moisture and mean thickness of Anita and Tina lentil seeds

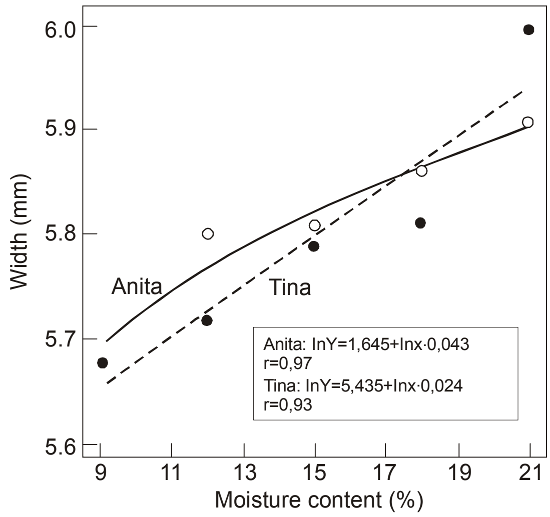

Fig. 17. Relationship between moisture and mean width of Anita and Tina lentil seeds

Analysis of variance permitted the calculation of coefficients of variation which for seed thickness form the range from 2.69 to 10,04% for both cultivars, and for seed width – from 4.63 to 7.42%. These are values that show low variability of the material under study.

4.5. Effect of moisture on the weight of 1000 seeds, porosity, density and on angles of repose and slide of seed in bulk

The mean values of physical properties of lentil seed in bulk are presented in Tables 11-13. Mean values of the weight of 1000 dry (9%) seeds of the Anita cultivar in the first and second years of the experiment were 44.63 g and 50.04 g, respectively, while those of Tina were 49.91 g and 46.52. This shows that the two cultivars responded in opposite ways to the differentiated weather conditions of the years of the study.

In final result, however, it was the Tina cultivar that bore the more shapely seeds after the two years.

Anita seed layer porosity was characterized by similar values (48.0 and 47.8%), as did that of Tina seed in the first year of the study (48.6%). In 2001, however, Tina seed showed less free spaces between the seeds (45.7%).

Table 11. Mean values of physical properties of ANITA lentil seed mass

Moisture (%)	2000 Year					2001 Year				
	Weight of 1000 seeds (g)	Porosity (%)	Density (kg m^{-3})	Angle of repose (°)	Angle of slip (°)	Weight of 1000 seeds (g)	Porosity (%)	Density (kg m^{-3})	Angle of repose (°)	Angle of slip (°)
9	44.63	48.0	784.5	29.0	27.0	50.04	47.8	792.0	30.0	28.0
12	45.79	48.3	776.0	26.5	27.0	50.35	46.9	781.0	26.5	29.5
15	46.66	49.1	763.0	25.5	27.5	52.01	46.6	772.5	27.5	29.0
18	48.49	49.4	752.0	26.0	28.0	54.49	47.7	754.0	29.0	29.0
21	51.43	50.7	711.0	30.5	29.0	57.07	47.9	746.5	27.0	28.5

Table 12. Mean values of physical properties of TINA lentil seed mass

Moisture (%)	2000 Year					2001 Year				
	Weight of 1000 seeds (g)	Porosity (%)	Density (kg m^{-3})	Angle of repose (°)	Angle of slip (°)	Weight of 1000 seeds (g)	Porosity (%)	Density (kg m^{-3})	Angle of repose (°)	Angle of slip (°)
9	49.91	48.6	789.0	27.0	27.0	46.52	45.7	783.0	34.5	31.0
12	52.48	50.4	736.0	31.0	27.0	51.62	46.9	784.0	31.5	27.0
15	52.76	49.7	749.5	29.5	29.5	53.89	46.9	762.0	29.0	26.5
18	56.32	50.0	727.5	33.0	31.0	57.69	47.3	752.5	28.0	28.0
21	58.09	51.3	708.5	38.5	36.0	58.48	47.7	747.0	28.0	26.0

Table 13. Mean values of physical properties of ANITA and TINA lentil seeds for the years 2000-2001

Moisture (%)	ANITA					TINA				
	Weight of 1000 seeds (g)	Porosity (%)	Density (kg m^{-3})	Angle of repose (°)	Angle of slip (°)	Weight of 1000 seeds (g)	Porosity (%)	Density (kg m^{-3})	Angle of repose (°)	Angle of slip (°)
9	47.34	47.9	788.2	29.5	27.5	48.21	47.2	786.0	30.7	29.0
12	48.07	47.6	778.5	26.5	28.2	52.05	48.6	760.0	31.2	27.0
15	49.34	47.8	767.7	26.5	28.2	53.32	48.3	755.7	29.2	28.0
18	51.49	48.5	753.0	27.5	28.5	57.00	48.7	740.0	30.5	29.5
21	54.25	49.3	728.7	28.7	28.7	58.28	49.5	727.7	33.2	31.0

Bulk density of dry seeds of Anita was lower in 2000 (784.5 kg m^{-3}) than in 2001 (792.0 kg m^{-3}). The situation was reversed in the case of Tina (789.0 and 783.0 kg m^{-3}), but here the difference between the years was less. In effect, after two years bulk density of Anita seeds was nearly 2 kg m^{-3} higher than that of Tina.

In the first year of the study, the angle of free repose for seeds of the Anita cultivar was 29.5°, and for those of Tina – 27.0°. In the second year, the values notable increased and were, respectively, 30.0° and 34.5°. The angle of slide for Anita was 2° lower than the angle or repose, while Tina showed identical values of the angles in 2000 and a 3.5° difference in the following year.

Increased moisture content caused a clear and systematic increase in the weight of 1000 seeds, up to the limit increments of 7 g for the Anita cultivar and 8 and 12 g for Tina (figure 18). That latter cultivar absorbed more water due to its larger seeds, and therefore, at the moisture level of 21% in the second year of the study, the weight of 1000 seeds of Tina was as much as 58.48 g.

Seed layer porosity also increased or displayed a tendency to increase, but within a much narrower range than the other features under discussion (figure 19). Between the extreme levels of moisture content, the margin of change increased from 0.1% (Anita, 2001) to 2,7% (Anita and Tina, 2000). Data for the two years indicate that for the Anita cultivar the feature changes with relation to moisture within a narrower range (1.4%) than for Tina (2.3%). This is a fact to be taken into account in seed drying, where seed layer porosity plays an important role by facilitating or inhibiting the flow of the drying agent or medium.

Bulk density of lentil seeds distinctly decreases with increasing seed moisture content, and this is true of both the cultivars (figure 20), with the differences reaching even up to 80.5 kg m^{-3} (Tina, 2000). Lower differences were observed in 2001 and did not exceed 45.5 kg m^{-3} (Anita). Values characterizing the two years of study show differences between extreme levels of seed moisture content attaining 60 kg m^{-3}.

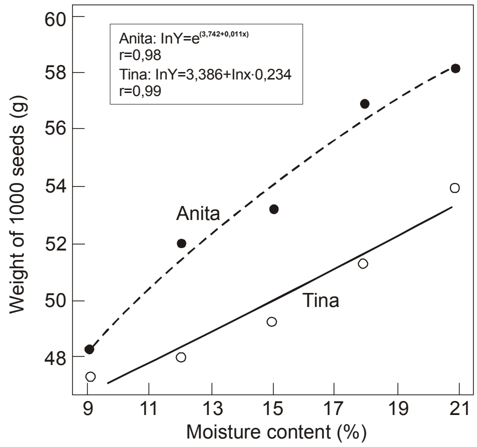

Fig. 18. Relationship between moisture and weight of 1000 seeds of Anita and Tina lentil varieties

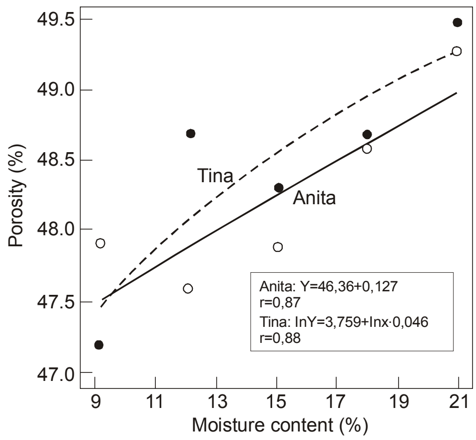

Fig. 19. Relationship between moisture and porosity of Anita and Tina lentil seed mass

Variability of the values of angles of repose and slide of lentil seed is highly significant in the determination of a variety of technological processes involved in the drying, cleaning, transport, reloading, and storage. The values of the angles are also related to seed moisture content. Their variation is less pronounced in the case of the Anita cultivar, and in 2000 showed a tendency to increase with increasing seed moisture. For the Tina cultivar, the values of the angles of repose and slide strongly increased with increasing moisture in the year 2000, and decreased in 2001. This was undoubtedly related with the condition of the seed

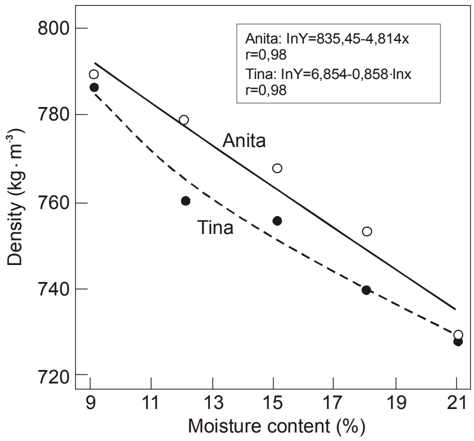

Fig. 20. Relationship between moisture and density of Anita and Tina lentil seeds

cover and with internal friction. The surface of the seed cover of lentil seeds has a specific character, as mentioned in subchapter 4.8. Other Features. One can assume that the condition of the seed cover may be affected not only by the content of water in the seeds, but also by the weather conditions prevailing during seed ripening and by the geometric features of the seed. Still another factor is the mutual orientation of seeds in the processes of seed pouring, characterized by the angles of repose and slip. The specific shape of lentil seeds appears to support this kind of interpretation of the results obtained.

4.6. Effect of moisture on the variation of the mechanical properties of individual seeds

A significant effect of moisture was observed in the case of studies on lentil seed resistance to damage caused by external loading. The lowest values of force causing damage to the seed cover (elastic force – the force that causes the first damage to the seed) were recorded for totally dry seeds (0%) (figure 21, 22, 26, 27, 31, 32, 36, 37). The cover of such seed got damaged the most easily, and that feature was observed with every kind of loading applied (in every test). Also the cotyledons of seeds with 0% moisture were more susceptible to damage caused by external loading, which was manifested by the lowest values of maximum force with relation to the values of that parameter recorded at high levels of seed moisture. That force caused cotyledon cracking. With increasing seed moisture, the values of the maximum force grew, as did those of the elastic force, reaching their maxima at seed moisture of 11%. At higher seed moisture levels the values of those parameters decreased. Such regularity was observed for both the Anita and Tina cultivars. It was confirmed in the kinds of tests and on material from both the years of the experiment. It should be emphasized that depending on the kind of test applied the differences recorded were either statistically significant or insignificant, nevertheless the tendencies mentioned occurred in all the combinations of the experiment (cultivars, years). The lowest mean value of the maximum force (13,8 N) was recorded for the Anita cultivar in the of penetration with ball tip at seed moisture of 0% in the year 2000, and the highest was noted for the same cultivar in the compression test of seed oriented with its plane of division perpendicular to the direction of compression, at seed moisture content of 11% in the year 2001 (116,8 N). The lowest value of that parameter recorded in the measurements of individual seeds was the value of 3.5 N (Tina, 2000, 0% moisture, test PP), and the highest was 188.2 N (Anita, 2001, 11% moisture, test PR).

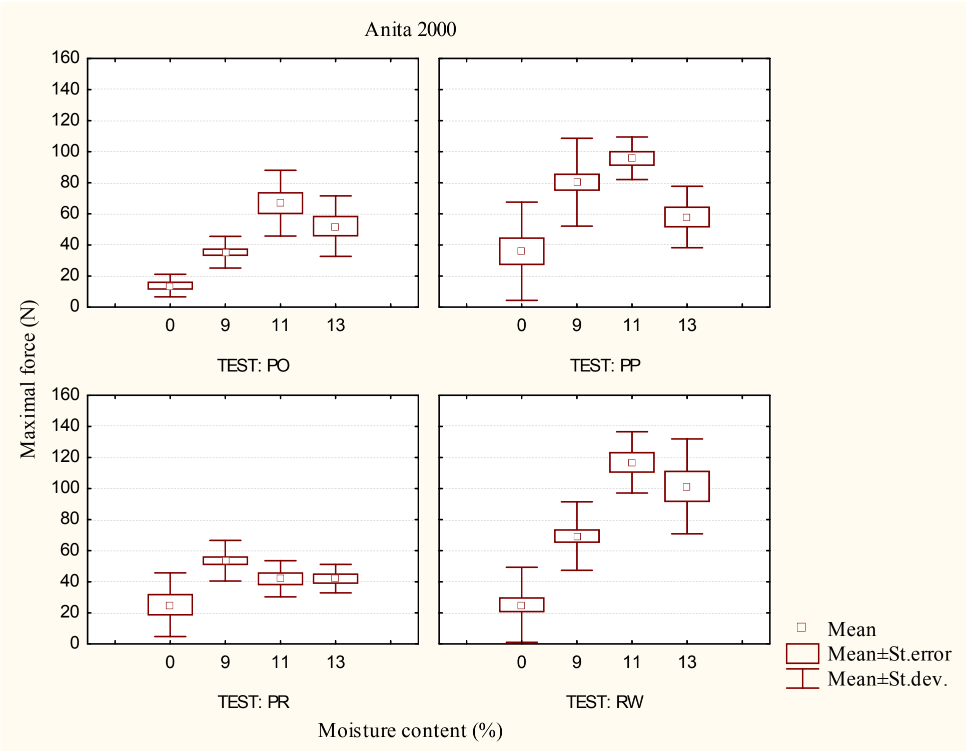

Fig. 21. The influence of seed moisture content on value of maximal force of lentil v. Anita from crop of year 2000 in four tests. Test PO – sphere penetrometer, test PP – flat penetrometer, test PR – compression of seed with cotyledon dividing plain perpendicular to loading direction, test RW – compression of seed with cotyledon dividing plain parallel to loading direction

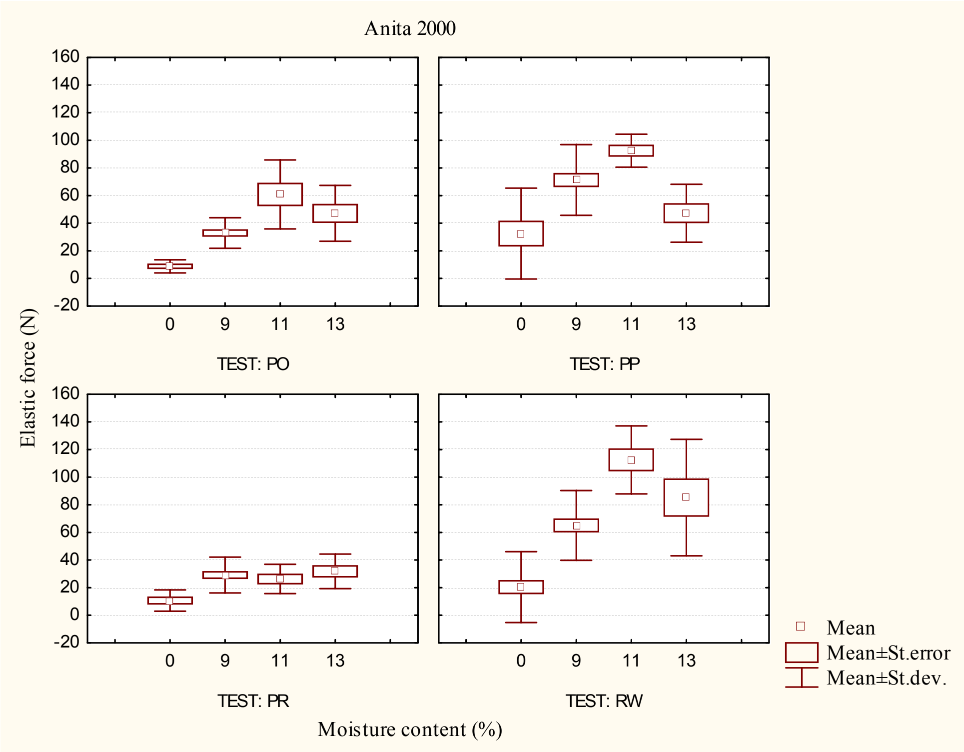

Fig. 22. The influence of seed moisture content on value of elastic force of lentil v. Anita from crop of year 2000 in four tests. Tests explanation as at fig. 21.

Comparing the results obtained in the preliminary and the main studies, a significant difference was observed in the changes of the force parameters (maximum and elastic). It was noted that the force parameter assumed maximum values at seed moisture level of 11%, while in the preliminary study no such maximum was observed. It is to be assumed that the difference resulted from differences in the features of the sowing material which was the object of the preliminary study. The seeds were better formed, more shapely, and their seed cover was less wrinkled as compared to that of seeds that were the material studied in the scope of the main study. Moreover, in the preliminary study only one type of test was performed, while the main study included four types of test and all of them confirmed the appearance of the aforementioned feature.

Like the force parameter, also strain assumed the lowest values at seed moisture of 0% and the values were significantly different from those observed at higher seed moisture levels. This is true both of the maximum strain and of the strain causing the first damage to the seed cover (figure 23, 24, 28, 29, 33, 34, 38, 39). With increasing seed moisture content, the values of the maximum strain and of the elastic strain grew systematically. Maximum values of both those parameters were noted at the highest level of seed moisture, i.e. at 13%. Differences in the strain values at the lowest and the highest moisture levels were statistically significant. Both the tendency to strain increase with increasing seed moisture and the significance of the changes were observed in all the types of tests applied and for both the lentil cultivars in both years. The mean values of the maximum strain fell within the range from 0.089 mm (Tina, 2000, 0% moisture, test RW) to 0.61 mm (Anita, 2001, 13% moisture, test RW). The lowest value of maximum strain recorded in a single test was 0.025 mm (Tina, 2000, 0% moisture, test PP), and the highest – 1.09 mm (Anita, 2001, 13% moisture, test RW).

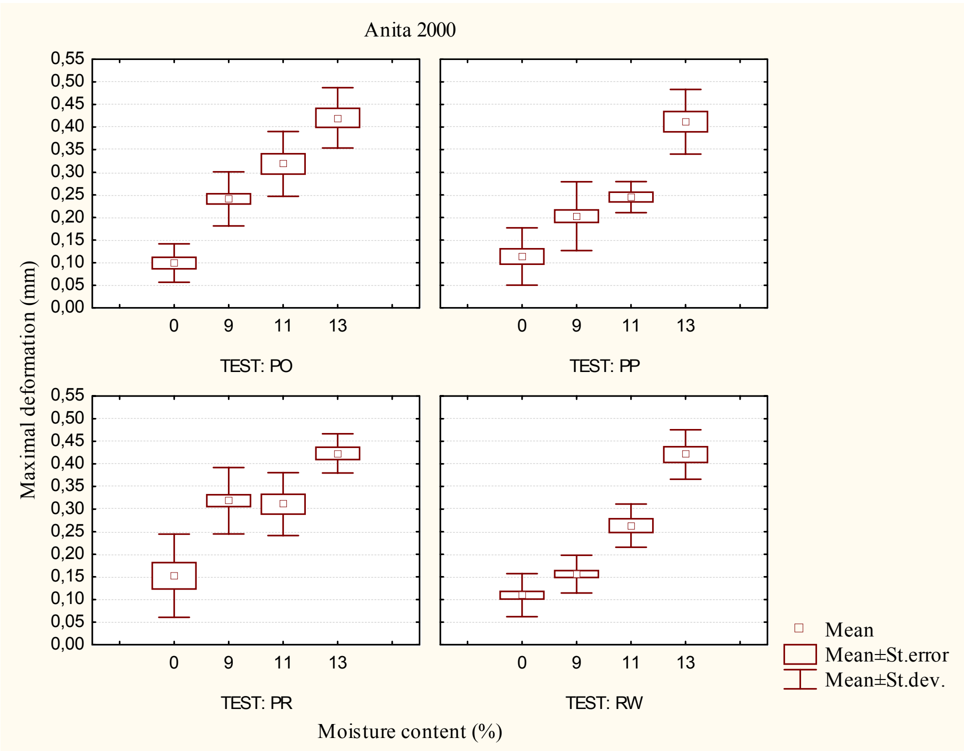

Fig. 23. The influence of seed moisture content on value of maximal deformation of lentil v. Anita from crop of year 2000 in four tests. Tests explanation as at fig. 21.

Also the values of work necessary to damage the seed were the lowest for the driest seed. The value of the parameter increased with increasing moisture, assuming the highest levels at the highest levels of moisture, i.e. at 13% (figure 25, 30, 35, 40). Attention should be drawn to the high values of confidence intervals for that parameter at the highest seed moisture and the lowest values of confidence intervals for completely dry seed. Increase in the value of work with increasing seed moisture was observed in all the types of tests conducted. The tendency was observed for both lentil cultivars studied, in both years of the study. Mean values of work fell within the range from 0.84 mJ (Anita, 2000, 0% moisture, test PO) to 24,94 mJ (Tina, 2001, 13% moisture, test PO). Values of work recorded in individual tests formed the range from 0.07 mJ (Tina, 2000, 0% moisture, test PP) to 77,62 mJ (Tina, 2001, 13% moisture, test PP).

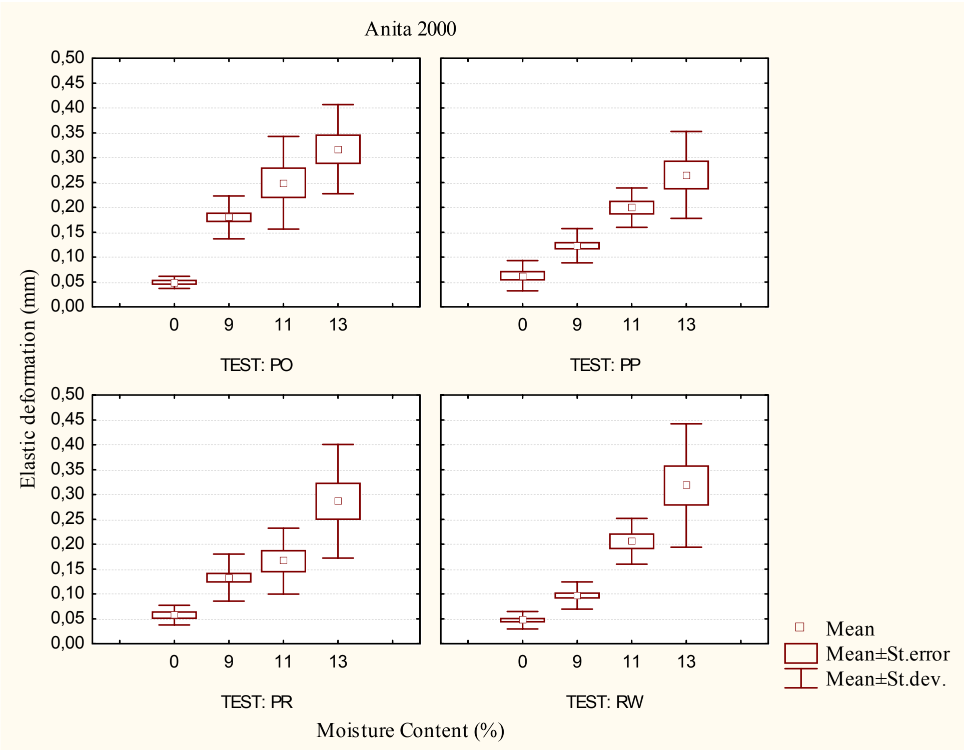

Fig. 24. The influence of seed moisture content on value of elastic deformation of lentil v. Anita from crop of year 2000 in four tests. Tests explanation as at fig. 21.

Comparing the two lentil cultivars, it should be stated that Anita was more resistant to seed cover damage. This is supported by the higher mean values of all the parameters studied – the tendencies concern primarily the maximum force and the elastic force, but also the corresponding strains as well as work.

No statistically significant differences were observed in the values of the parameters studied for the two cultivars in successive years. Seeds originating from the crop of the years 2000 and 2001 were characterized by similar strength features.

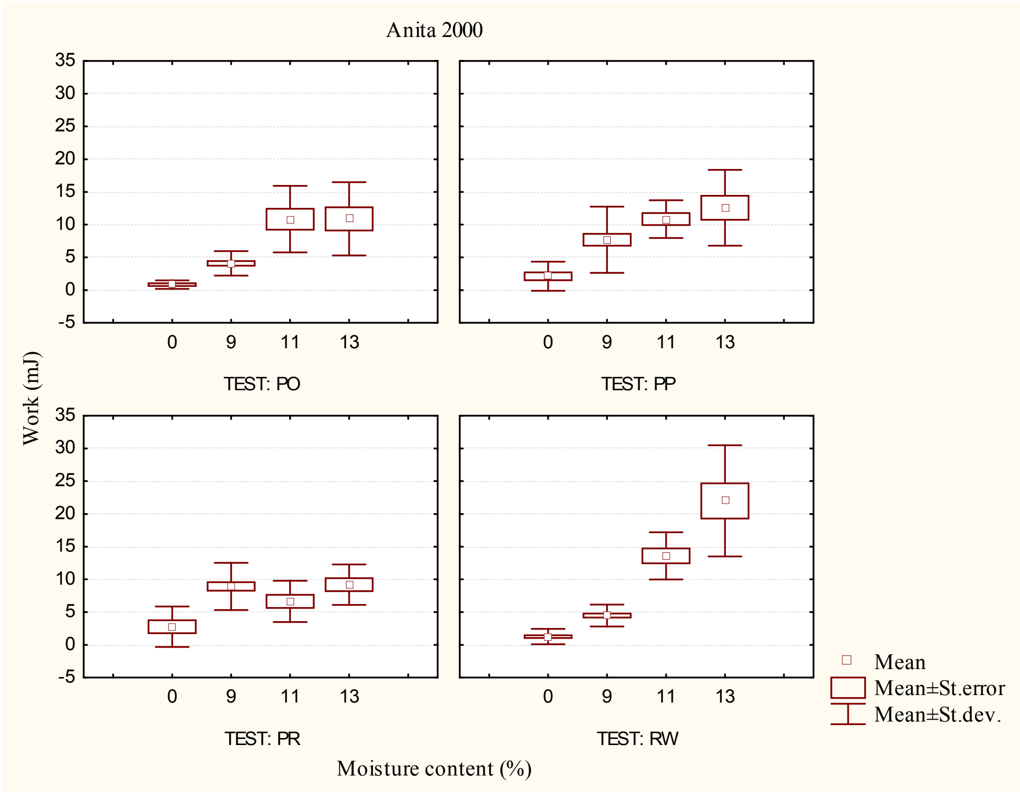

Fig. 25. The influence of seed moisture content on value of work required for seed braking of lentil v. Anita from crop of year 2000 in four tests. Tests explanation as at fig. 21.

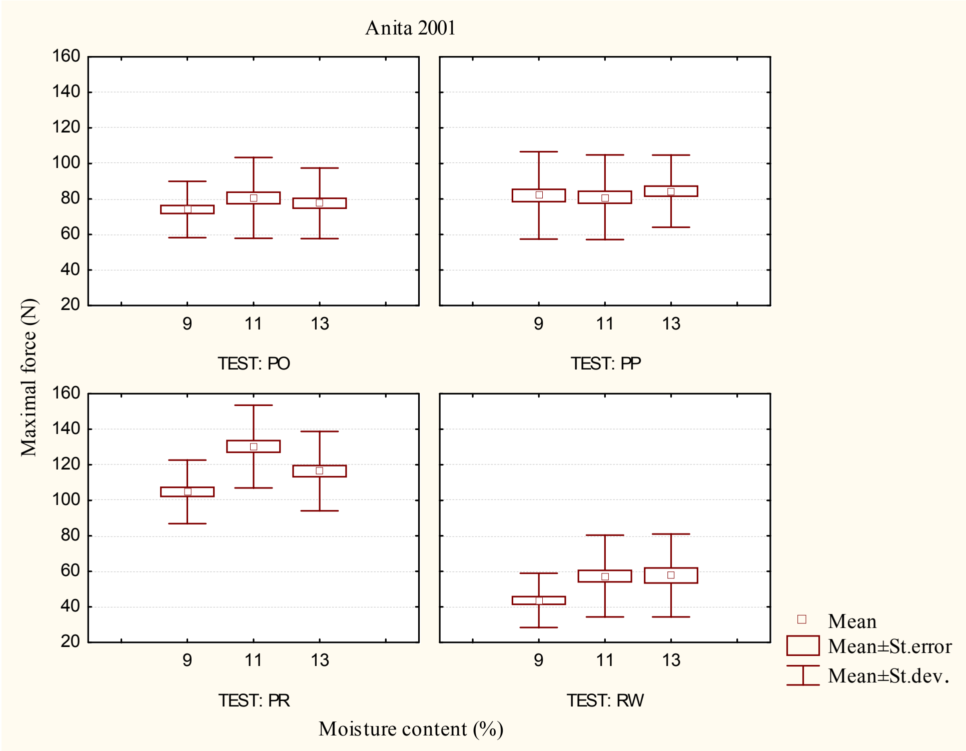

Fig. 26. The influence of seed moisture content on value of maximal force of lentil v. Anita from crop of year 2001 in four tests. Tests explanation as at fig. 21.

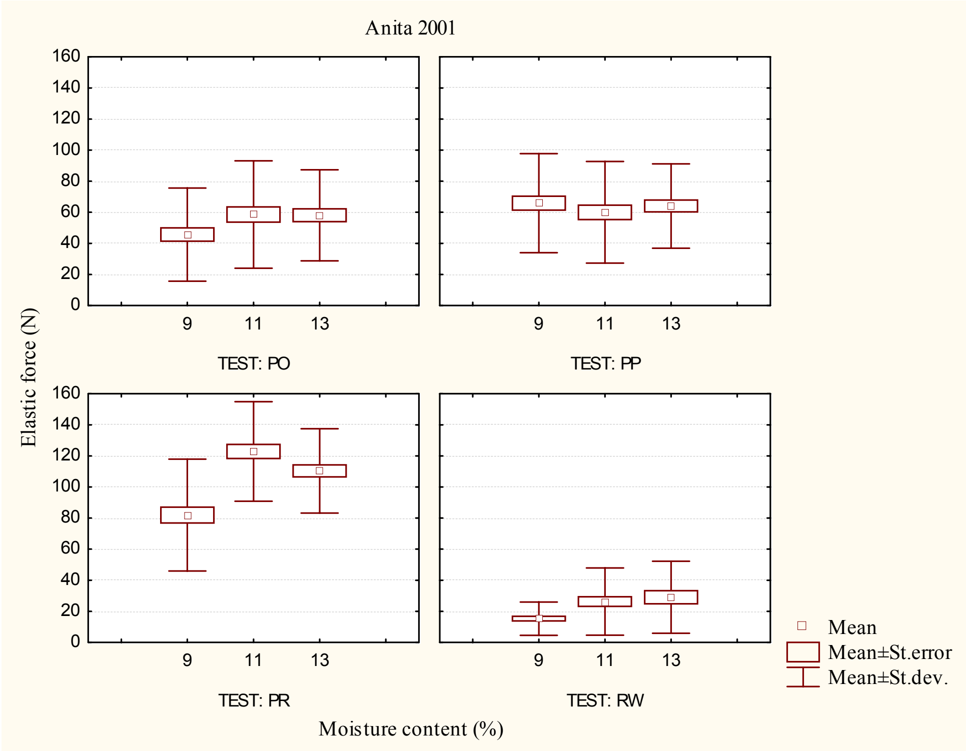

Fig. 27. The influence of seed moisture content on value of elastic force of lentil v. Anita from crop of year 2001 in four tests. Tests explanation as at fig. 21.

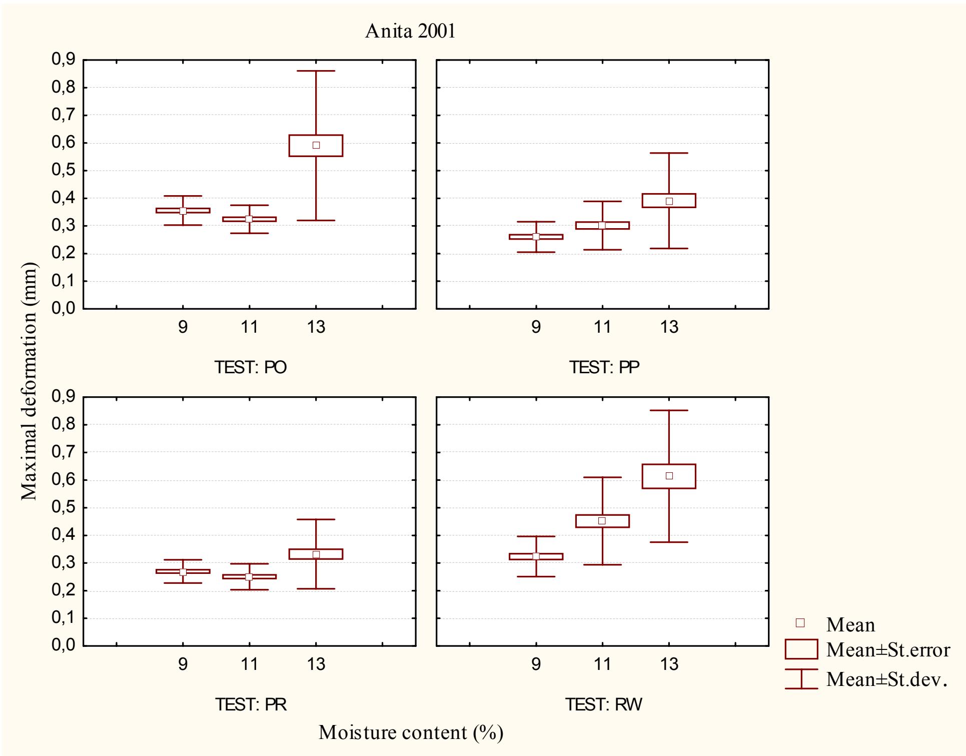

Fig. 28. The influence of seed moisture content on value of maximal deformation of lentil v. Anita from crop of year 2001 in four tests. Tests explanation as at fig. 21.

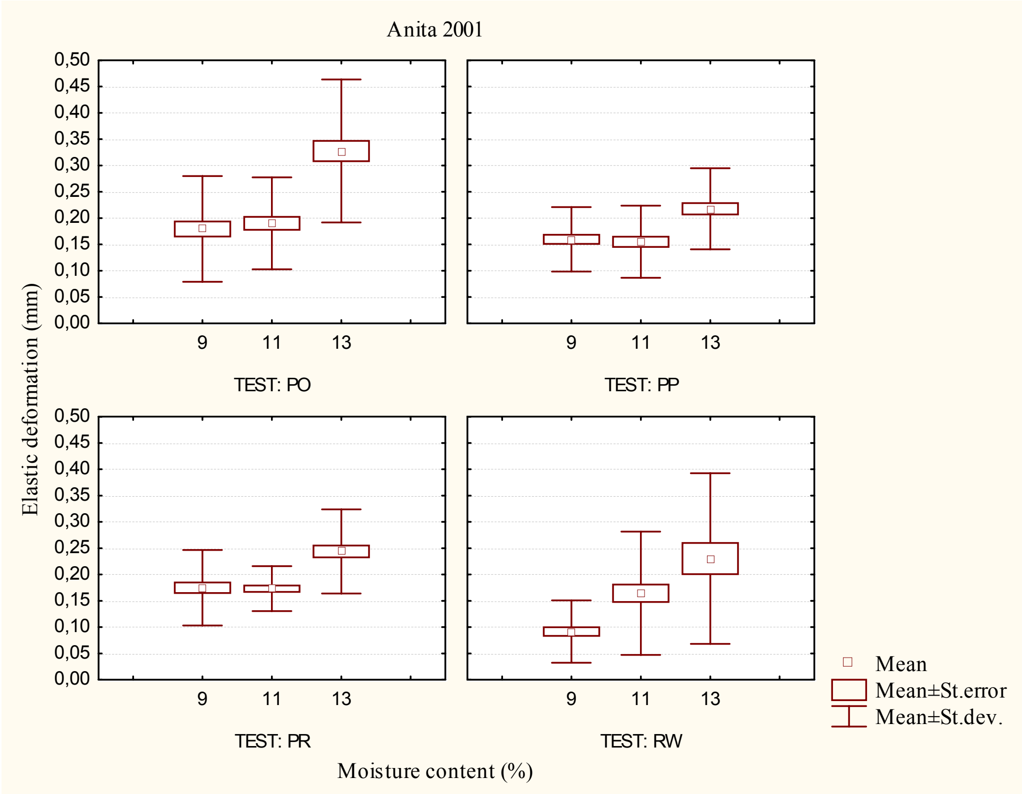

Fig. 29. The influence of seed moisture content on value of elastic deformation of lentil v. Anita from crop of year 2001 in four tests. Tests explanation as at fig 21.

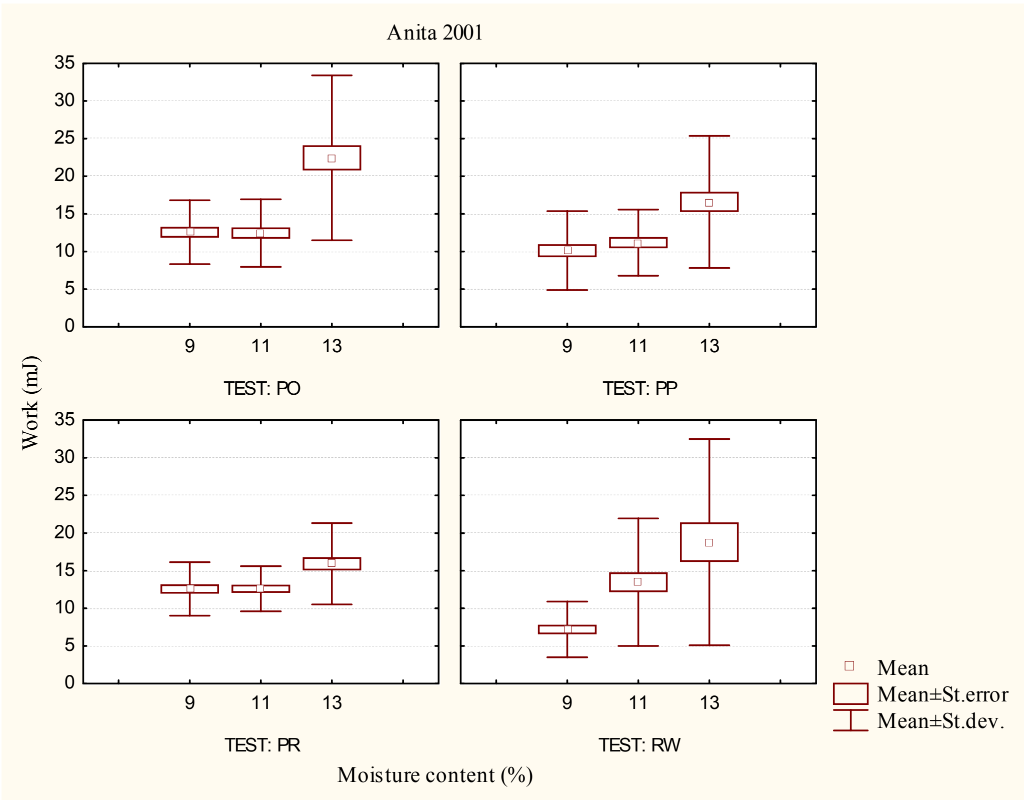

Fig. 30. The influence of seed moisture content on value of work required for seed braking of lentil v. Anita from crop of year 2001 in four tests. Tests explanation as at fig. 21.

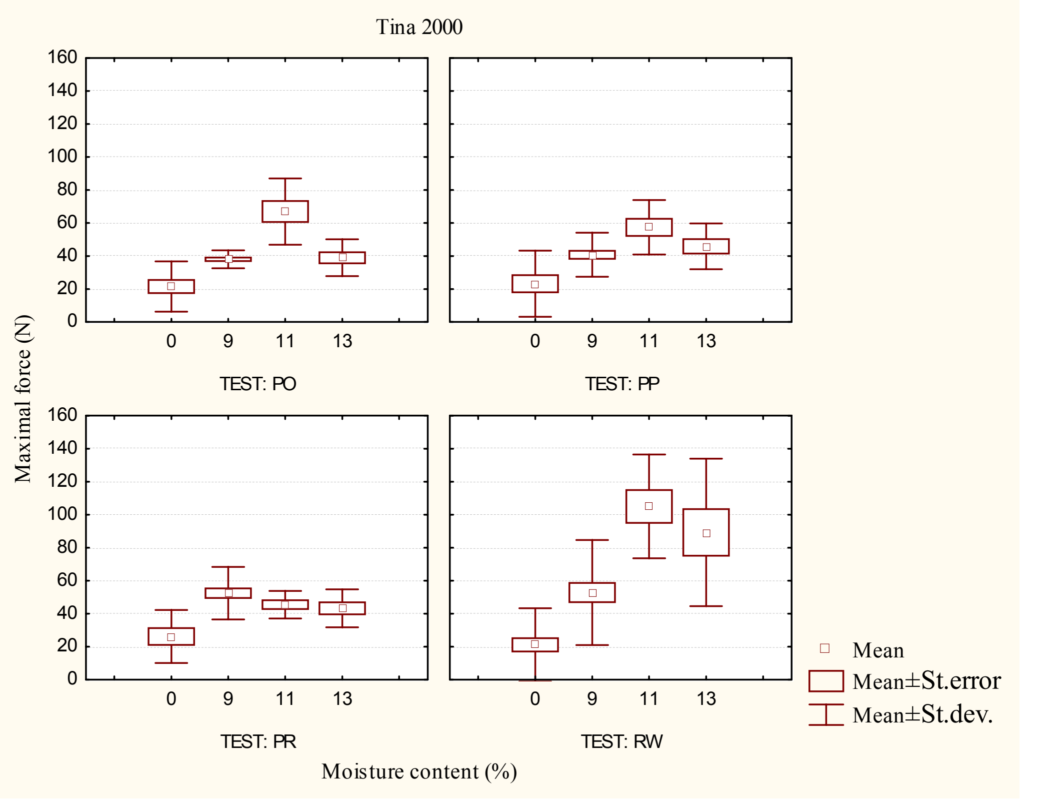

Fig. 31. The influence of seed moisture content on value of maximal force of lentil v. Anita from crop of year 2000 in four tests. Tests explanation as at fig. 21.

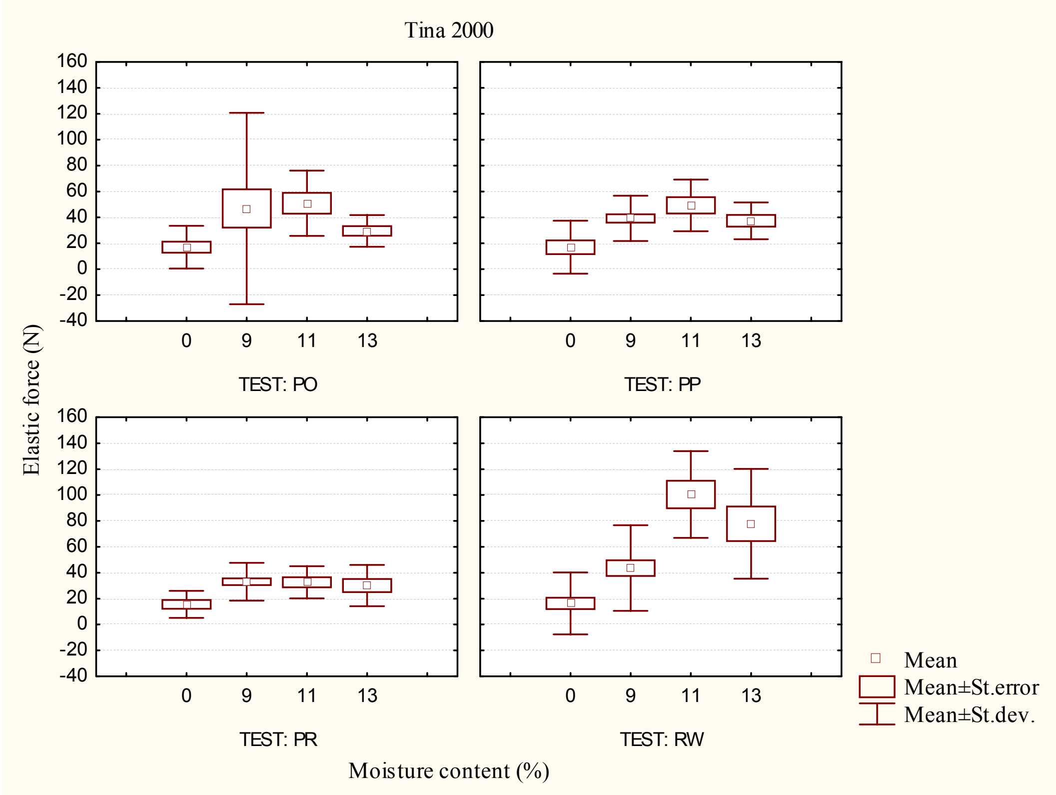

Fig. 32. The influence of seed moisture content on value of elastic force of lentil v. Tina from crop of year 2000 in four tests. Tests explanation as at fig. 21.

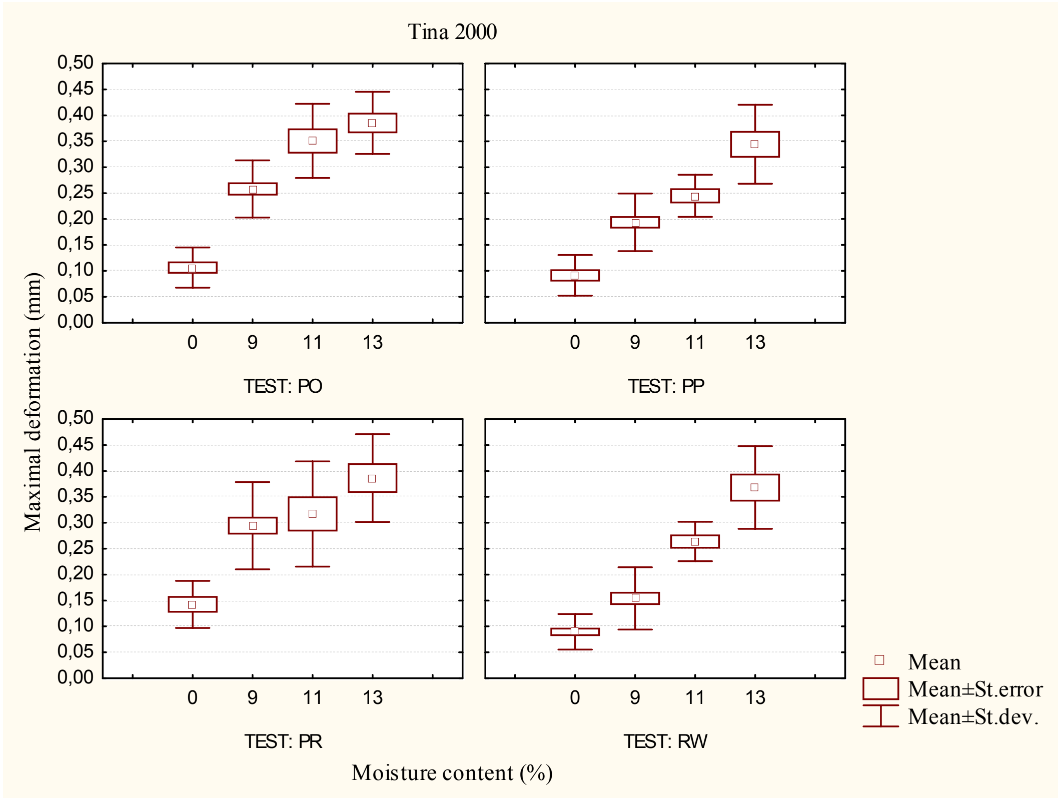

Fig. 33. The influence of seed moisture content on value of maximal deformation of lentil v. Tina from crop of year 2000 in four tests. Tests explanation as at fig. 21.

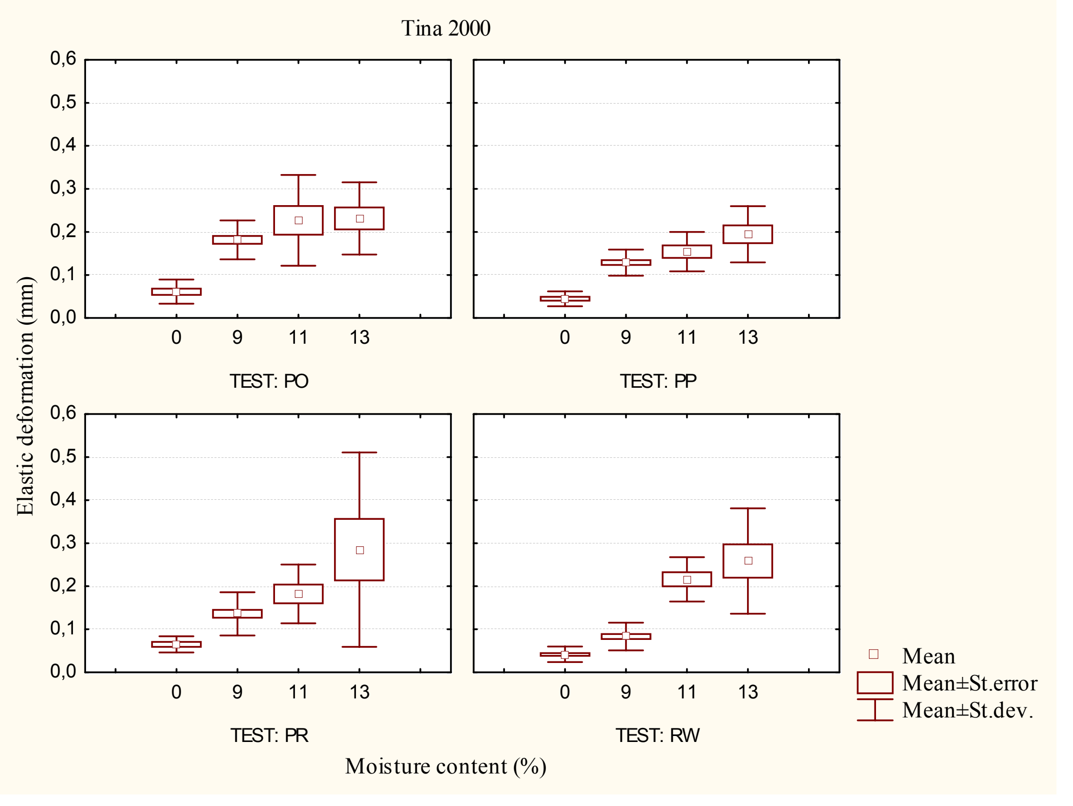

Fig. 34. The influence of seed moisture content on value of elastic deformation of lentil v. Tina from crop of year 2000 in four tests. Tests explanation as at fig. 21.

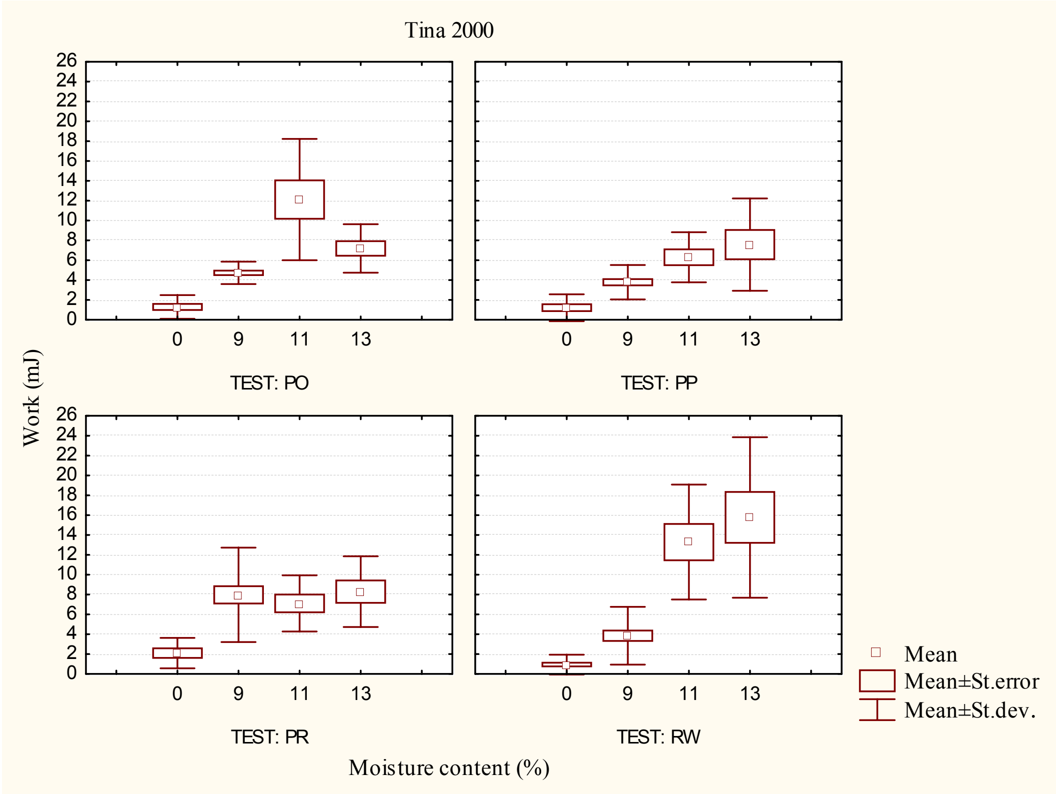

Fig. 35. The influence of seed moisture content on value of work required for seed braking of lentil v. Tina from crop of year 2000 in four tests. Tests explanation as at fig. 21

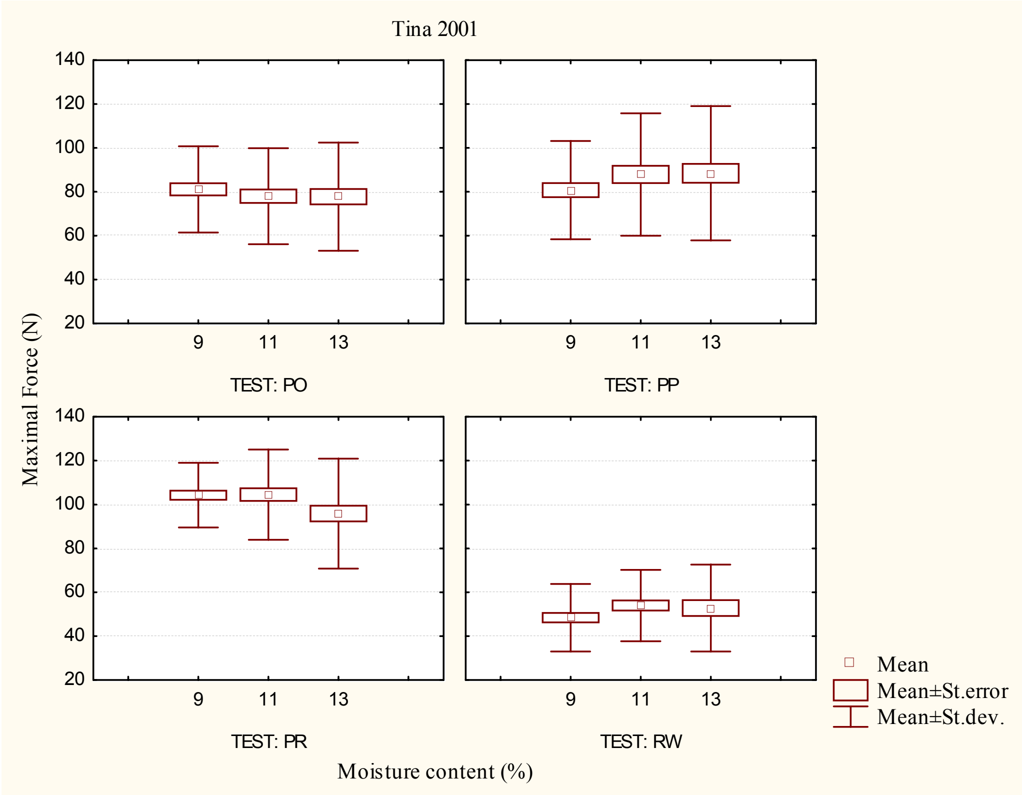

Fig. 36. The influence of seed moisture content on value of maximal force of lentil v. Tina from crop of year 2001 in four tests. Tests explanation as at fig. 21.

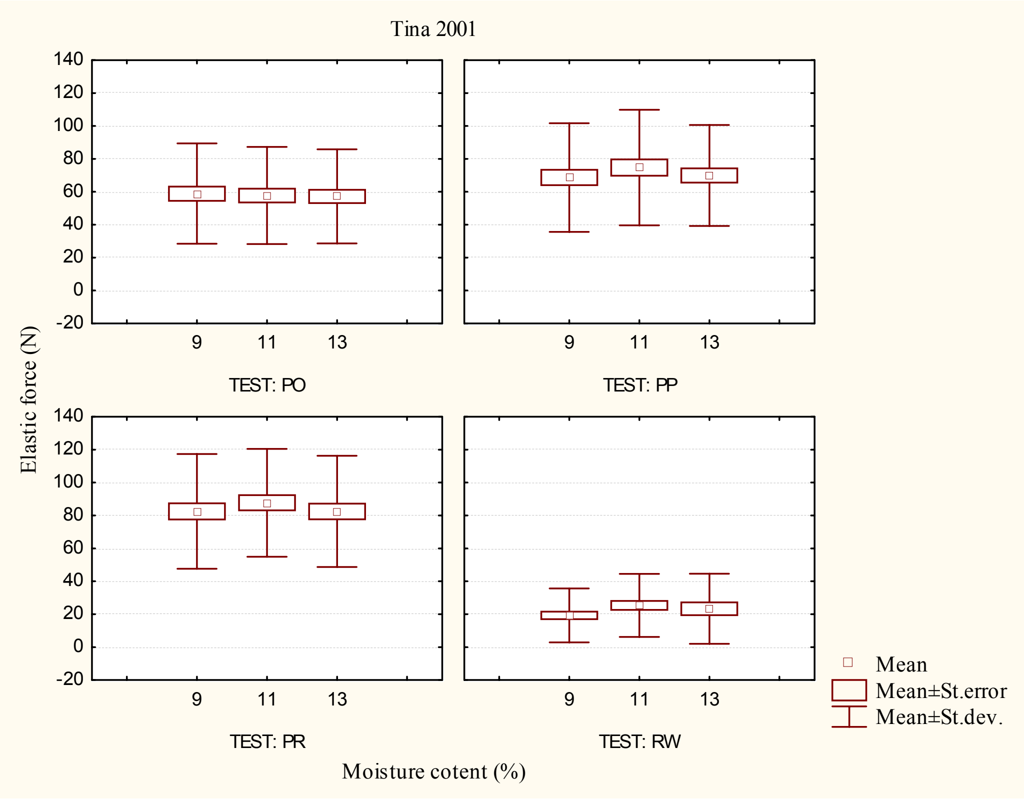

Fig. 37. The influence of seed moisture content on value of elastic force of lentil v. Tina from crop of year 2001 in four tests. Tests explanation as at fig. 21

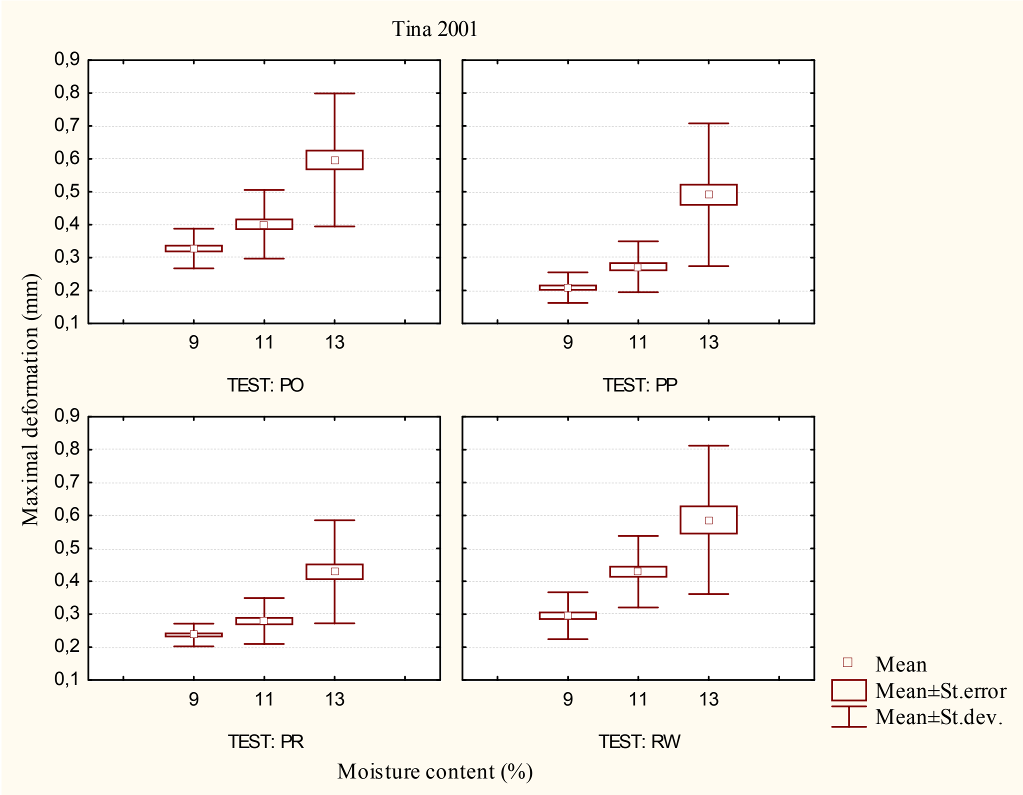

Fig. 38. The influence of seed moisture content on value of maximal deformation of lentil v. Tina from crop of year 2001 in four tests. Tests explanation as at fig. 21.

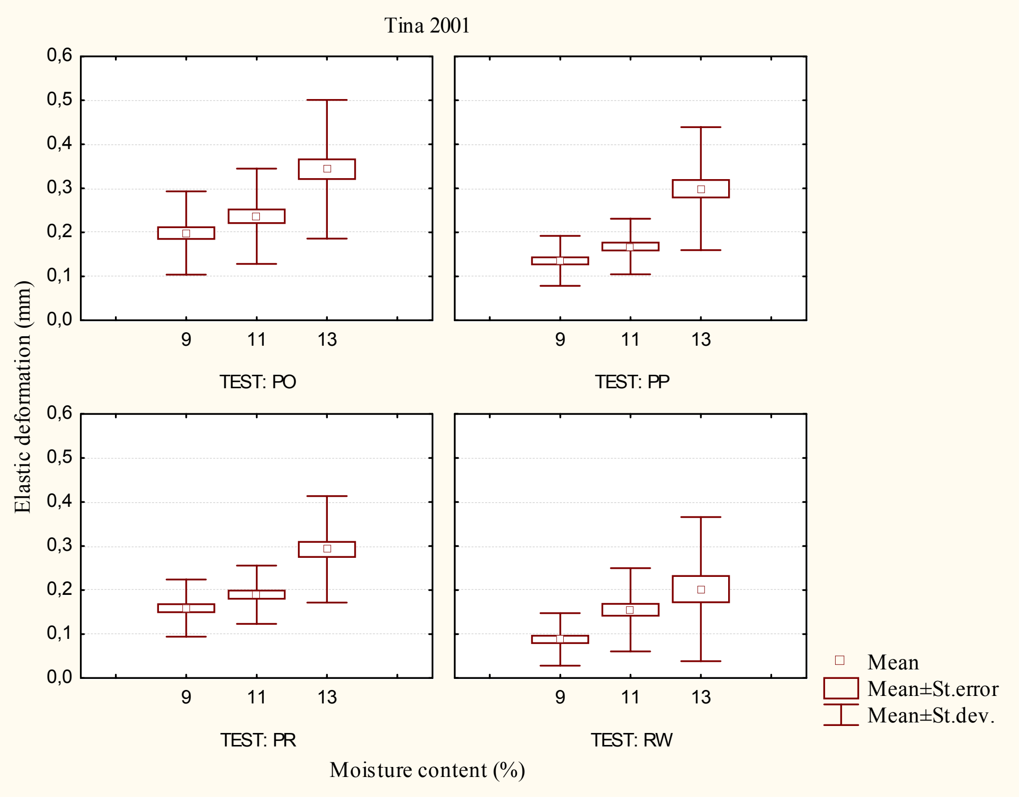

Fig. 39. The influence of seed moisture content on value of elastic deformation of lentil v. Tina from crop of year 2001 in four tests. Tests explanation as at fig. 21.

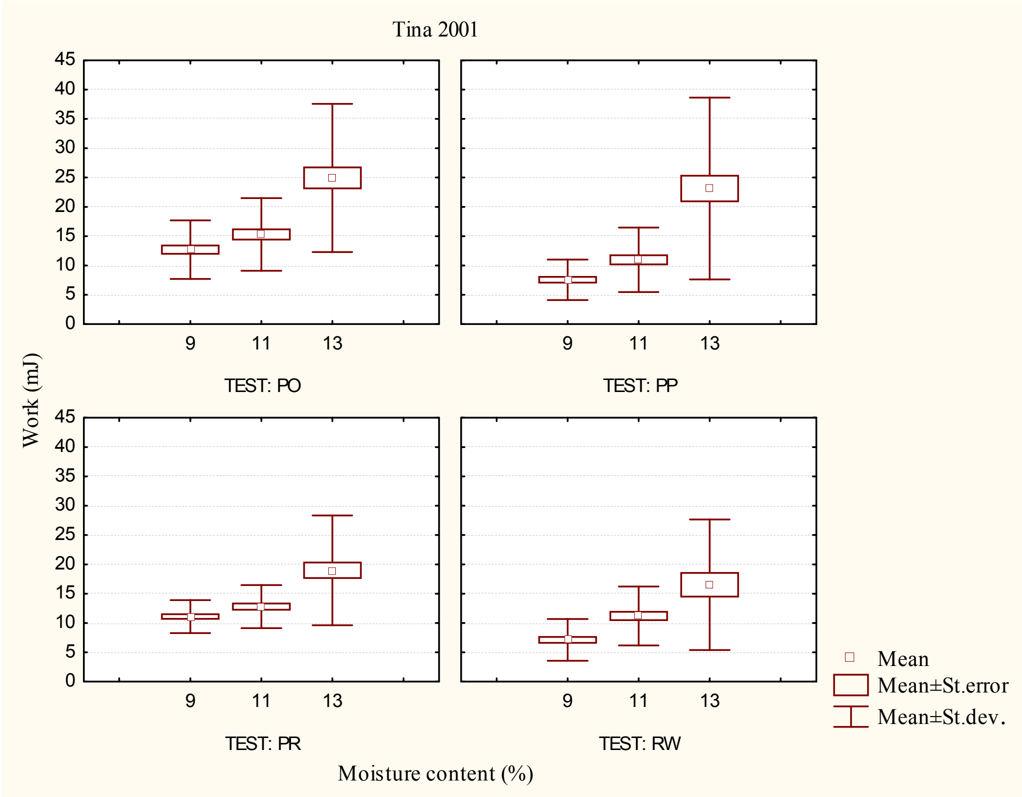

Fig. 40. The influence of seed moisture content on value of work required for seed braking of lentil v. Tina from crop of year 2001 in four tests. Tests explanation as at fig. 21

As to the evaluation of the tests employed in the study, all of them proved suitable for the estimation of lentil seed susceptibility to damage caused by external loading. It would be hard to indicate one test that would be the most suitable or characterized by the highest sensitivity for the type of study. Each of the test provided the possibility of precise determination of the parameters studied and of comparing the parameters with reference to seed moisture content or to cultivar features.

4.7. Effect of moisture on the mechanical properties of seed in bulk

Curves of stress relaxation, interpreted with the Maxwell model, permitted the determination of the coefficients of elasticity, E_1 and E_2, and of viscosity – η_1; η_2 (table 14). For air-dry seeds the coefficient referring to the elastic part of strain assumed the highest values and decreased with increasing seed moisture. Likewise, the coefficient referring to the viscous part of strain decreased with increasing moisture, assuming the highest values at seed moisture content of 9%.

Table 14. Coefficient values of two-element Maxwell model.

Moisture	ANITA		TINA	
(%)	E_1 ; E_2 (Pa)	η_1 ; η_2 (Pa s)	E_1 ; E_2 (Pa)	η_1 ; η_2 (Pa s)
9	$2.73\ 10^6$; $1.56\ 10^7$	$1.35\ 10^8$; $8.23\ 10^{10}$	$2.76\ 10^6$; $1.69\ 10^{10}$	$1.78\ 10^8$; $8.03\ 10^{10}$
12	$2.46\ 10^6$; $5.55\ 10^6$	$1.12\ 10^8$; $1.43\ 10^{10}$	$1.26\ 10^6$; $2.97\ 10^6$	$6.03\ 10^7$; $6.96\ 10^9$
15	$8.16\ 10^5$; $1.44\ 10^9$	$3.76\ 10^7$; $2.28\ 10^9$	$1.03\ 10^6$; $2.03\ 10^6$	$4.83\ 10^7$; $3.70\ 10^9$
18	$4.50\ 10^5$; $7.34\ 10^5$	$2.09\ 10^7$; $9.82\ 10^8$	$6.44\ 10^5$; $1.06\ 10^6$	$3.16\ 10^7$; $1.59\ 10^9$
21	$1.73\ 10^5$; $2.31\ 10^5$	$7.51\ 10^7$; $2.84\ 10^8$	$2.35\ 10^5$; $3.36\ 10^5$	$1.06\ 10^7$; $4.10\ 10^8$

The ranges of values of the coefficients of elasticity were, respectively: E_1 from $1,73x10^5$ Pa to $2,73x10^6$ Pa; E_2 from $2,3x10^5$ Pa to $1,56x10^7$ Pa in the case of Anita, and for Tina – E_1 from $2,35x10^5$ Pa to $2,76x10^6$ Pa; E_2 from $3,36x10^5$ Pa to $1,69x10^7$ Pa. The ranges of values of the coefficients of viscosity were as follows: η_1 from $7,51x10^7$ Pa s to $1,35x10^8$ Pa s, η_2 from $4,84x10^8$ Pa s to $8,23x10^{10}$ Pa s for the Anita cultivar, and the corresponding limit values for Tina were: η_1 $1,06x10^7$ and $1,78x10^8$ Pa s, and η_2 $4,1x10^8$ and $8,03x10^{10}$ Pa s.

4.8. Other features

Te structural properties of lentil seed covered were determined. The thickness of the seed cover was determined on the basis of structural analysis in scanning microscopy. It was found that the layer of palisade cells of lentil seed cover is much thinner than in most species of leguminous plants and does not exceed 25 µm (photo 17). Cells of the palisade layer are separated from cells of spongy parenchyma by a layer of support cells whose thickness does not exceed 5 µm (only in the region of the germ axis it can be up to 12 µm), and hence the layer cannot have any significant effect on the strength of lentil seed cover. The surface of the seed cover is verrucose in character (photo 18). The papilla or warts on the seed cover surface have diameters from 0.8 to 2,5 µm, and the distances between them form spaces ranging from 1.5 to 4,0 µm. This is very important for easy absorption of water, as opposed to other leguminous plant species. However, the thickness of the seed cover indicates its low mechanical strength. This was confirmed by additional measurements in compression test on lentil and soybean seeds, in which the seed cover thickness of the latter varied from 70 to 115 µm. Lentil seeds sustained damage at force values lower by factors of nearly three (Anita) and over two (Tina) as compared to soybean.

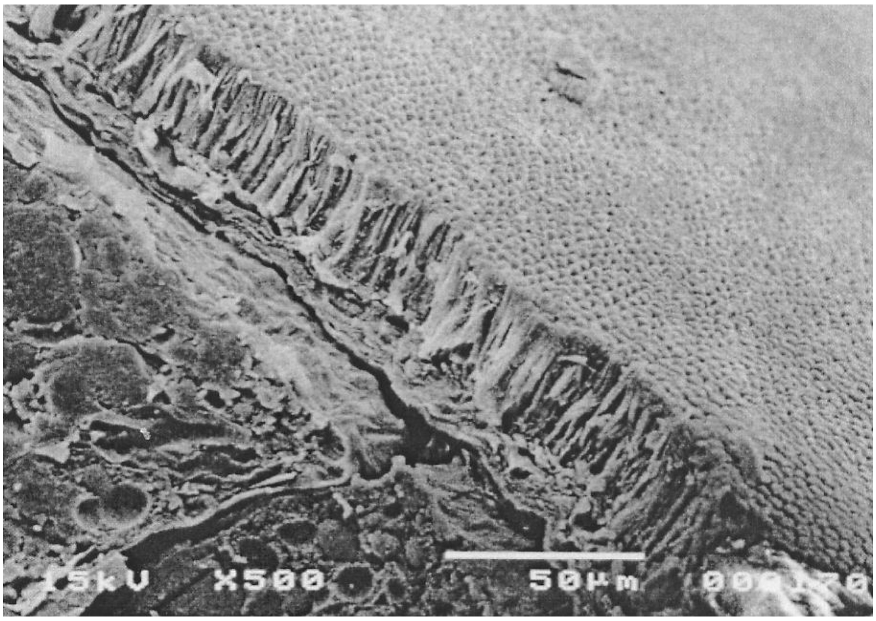

Photo 17. Seed cover of the Tina variety lentil seed

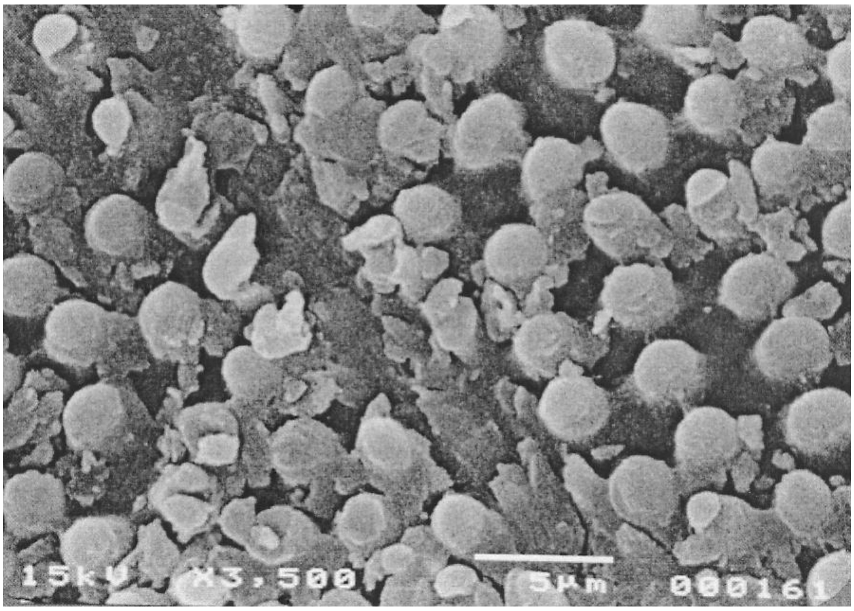

Photo 18. Surface of seed cover of the Tina variety lentil seed

5. AGROPHYSICAL BASES OF OBTAINING LENTIL SEED OF GOOD QUALITY

The study of the biometric features of lentil plants and of the physical properties of pods, of individual seeds (including the geometric features), of the weight of 1000 seeds, porosity, bulk density, angles of repose and of slide, and of the resistance of the seed to mechanical loading, permitted the results obtained to be analysed with a view to better knowledge on the one hand, and – on the other – to a search for solutions that would enable maximum possible limitation of qualitative and quantitative losses of lentil seed in the course of harvest and post-harvest processing.

So far, lentil has been grown in Poland on small areas and harvested by hand. In recent years, after numerous studies, it has been accepted a highly valuable "health food" with very good nutritional quality. Two Polish cultivars have been bred, but difficulties involved in the growing and harvesting of lentil caused that Polish companies import lentil seed that enjoys notable interest on the part of the consumers.

Polish producers of lentil encounter considerable problems in harvesting lentil. Combines used in this country are usually adapted for cereal harvest and, with certain modifications, also for harvesting rape and other non-cereal crops. Lentil requires also the adaptation of the harvester, and primarily of the repeating header used also for soy harvest. As shown in the study, lentil pods are set very low above soil surface. The mean value of the lowest pod of the Anita cultivar in the year 2000 (spring drought) did not reach even 15 cm. Combine harvest of such a cultivar entails very high quantitative losses of seed, especially when the plants are inclined and the pods touch the ground. In turn, every plant gathering element of harvesting machinery causes pod cracking. The Tina cultivar proved to be better suited for mechanical harvest, as irrespective of the weather conditions its lowermost pods were located at the height of 23.3-25.9 cm.

Lentil pods crack very easily. Ripe fruits crack already at the application of force of 0.7-0.9 N. Apart from that, spontaneous seed shedding occurs during the ripening, especially in windy conditions. Preparations for plant spraying used in the course of the study, Spodnam and potato starch, notably improved the resistance of the pods to cracking (by from 17 to 37%). Due to the fact that the spraying should be applied before the harvest (8-14 days, depending on the kind of preparation), technological paths on the plantation should foreseen already at the time of sowing.

Lentil seeds are round flattened lens-like. Their average thickness (for the crop obtained in our own experiments) varied, depending on the cultivar, year, and moisture, from 2.21 to 2,66 mm, and their width (diameter) from 5.61 to 6.08 mm. The weight of 1000 seeds, 44.6-58.5 g, is somewhat higher for the Tina cultivar which has more shapely seeds. Bulk porosity of the seed, so important from the viewpoint of the seed drying industry, fell within the range of 46.6-51.3% and increased with increasing seed moisture, while bulk density showed a clear tendency to decrease. The angles of repose and slide had a general tendency to increase with increasing seed moisture. The mean values of the angle of repose formed the range from 25.5º to 38.5º, and those of the angle of slide – from 26.5 to 36.0º. These values were notably differentiated by seed moisture and by the condition of the seed cover which is very thin and responds very fast to drying by getting wrinkled (already at 9%), and rapidly absorbs water during wetting. Therefore, that variability must be taken into account in post-harvest processing, and especially in transport and storage.

The resistance of individual seeds to mechanical loading depends significantly on the seed moisture. Dry seeds are most easily damaged, and their resistance increases with increasing moisture reaching the highest level at seed moisture of 11%. The ranges of parameters corresponding to seed damage are as follows: for the maximum force from 3.47 N to 188.18 N, for maximum strain from 0.025 mm to 1.09 mm, and for work from 0.07 mJ to 77,62 mJ within the full range of seed moisture covered in the study. The respective intervals of confidence for those parameters at seed moisture of 0% are as follows: maximum force from 20.3 N to 27.6 N, maximum strain from 0.1 mm to 0.12 mm and work from 1.15 mJ to 1,68 mJ. For seed moisture content of 11%, at which the seeds showed the highest resistance to external loads, the respective intervals of confidence for the particular parameters are the following: for the maximum force from 79.7 N to 85.5 N, for the maximum strain from 0.32 mm to 0.34 mm, and for work from 11.6 mJ to 12.58 mJ. When subjected to compression, seeds with moisture content above 13% already show plastic properties and the characteristic points describing the strength of a biological material are not obtained. Seeds of the Anita cultivar are more resistant to mechanical loads than seeds of Tina. In the successive years of the study, no statistically significant differences were found in the mechanical parameters describing the strength features of individual seeds.

Resistance to mechanical loads is a fundamental parameter and an index of the physical quality of seeds. Exceeding the limit force values results in unavoidable damage, reducing the quality of the whole batch of seeds. Hence, from the practical point of view, care must be taken both during the harvest and in the post-harvest processing to avoid damage to seed cover and cotyledons, and when collecting moist seeds, to prevent plastic deformation. In lentil seed storage in bulk, in turn, it should be kept in mind that both the elasticity of the seed and its viscosity decreases with increasing moisture.

6. CONCLUSIONS

The studies and their results permitted the formulation of the following conclusions:

1. The methods used, both those newly developed and those adapted for the requirements of the studies, allowed the determination of the agrophysical properties of lentil within the full range of their variability resulting from internal and external factors.
2. Seeds of the sowing material were characterized by the following features:
   - geometric features only slightly differentiate dry seed of the Tina and Anita cultivars, though the former has slightly thicker seeds and the latter somewhat wider;
   - weight of 1000 seeds is somewhat higher for Tina (49.36 g) than for Anita (48.05 g),
   - bulk density of seed increases with decreasing moisture reaching the values of 806 kg m^{-3} (Tina) and 795 kg m^{-3} (Anita), while porosity decreases to the level of 45.3-44,0%,
   - values of the angle of repose are lower than those of the angle of slide and fall within the range of 23-24°, the highest values being those for seed with the highest moisture content;
   - the structure of dry seeds of Tina is damaged at an average force of 96 N, and that of Anita seed at 125 N; when dry the seeds are characterized by elastic-brittle properties and with increasing moisture (at constant seed

deformation of 0.25 mm) the force values drastically drop, reaching a minimum of less than 10 N at moisture levels above 15%, when the seeds display visco-plastic properties and are subject to permanent deformations.

3. Average height of plants of the Anita cultivar was 46.2 cm, and of those of Tina Tina 48.8 cm. In this respect, plants of the Tina cultivar were more uniform.

4. In the first year of the study, the average number of branches of both cultivars was not less than 4.5, while in the second year it was notably lower (2,2-2,8).

5. Anita had pods set the lowest, on average at 19.1 cm from soil surface, while the corresponding value for Tina was 24.6 cm. Therefore, the latter cultivar is better suited for mechanical harvest.

6. In the first year of the study the average number of pods per plant of both cultivars oscillated around 40. In the second year the number of pods per plant was somewhat lower (Anita 32, and Tina 35.4).

7. Average seed yield from 1 m^2 for the Anita cultivar was 129.2 g and that for Tina 131,7 g, the yields being higher in the second year.

8. Spontaneous seed shedding during plant ripening reached the level of 3% of the yield. Further seed shedding occurred during the harvest.

9. Lentil pods crack already after the application of a force of 0.7-0.9 N. The application of plant spraying with Spodnam and potato starch preparations significantly improved the resistance of pods to cracking (by from 17 to 37%).

10. The weight of 1000 seeds, forming the range from 44.6 to 58.5 g, was somewhat higher in the case of the Tina cultivar, as was the case with the sowing material. Average thickness of lentil seeds, depending on the year, the cultivar, and the seed moisture, varied from 2.21 to 2.66 mm, and seed width (diameter) varied from 5.61 to 6.08 mm. These features were described with normal distributions. Both in the sowing material and in the material used in the main study Tina was characterized by thicker seeds, while there was no difference between the cultivars in terms of seed width. Seeds of the Tina cultivar were more shapely.

11. Seed porosity is bulk fell within the range of 46.6-51.3% and tended to increase with increasing seed moisture, while bulk density of dry seed had the values of 788.2 kg m^{-3} (Anita) and 786.0 kg m^{-3} (Tina) and clearly decreased with increasing seed moisture.

12. Mean values of the angle of repose formed the range of 25.5-38.5^o and those of the angle of slide 26.5-36.0^o and tended to increase with increasing seed moisture. The values are notable differentiated not just by seed moisture but also by the condition of seed cover which, being very thin, responds rapidly even to changes in the relative air humidity.

13. The resistance of individual seeds to mechanical loads depends significantly on their moisture content. Most susceptible to damage are dry seeds, and with increasing moisture their resistance to damage grows reaching a maximum at the

moisture of 11%. The ranges of variability of parameters corresponding to seed damage are the following: work from 0.07 mJ to 77,62 mJ, maximum force from 3.47 N to 188,18 N, and strain from 0.025 mm to 1.09 mm.

14. During compression, seeds with moisture content above 13% already display plastic properties and the characteristic points describing the strength of a biological material are not obtained.

15. Seeds of the Anita cultivar are more resistant to mechanical loads than seeds of Tina.

16. In successive years, no statistically significant differences were found in the values of parameters describing the strength properties of individual seeds.

17. The application of the Maxwell model permitted the calculation of the coefficients of elasticity and viscosity whose values decreased with increasing seed moisture content.

18. Determination of the biometric features of plants and of the physical properties of lentil seeds – apart from the cognitive aspects – allows the selection of data of the highest importance for the development of agrophysical bases for the obtaining of lentil seed of good quality.

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