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RHEOLOGICAL AND PHYSIOLOGICAL PROPERTIES OF PEA SEEDS (*PISUM SATIVUM L.*) OF DIFFERENT MOISTURE CONTENTS BEING STRESSED UNDER QUASI-STATIC LOAD

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A b s t r a c t. Pea seeds of three varieties were conditioned to a moisture content between 11.5 and 19.5 %. With a specially adapted universal instrument for strength testing (INSTRON) single seeds were compressed under quasi-static load while recording force and deformation until an a priori desired value of energy was applied. The physical shape of the stressed seeds was evaluated by visual examination and by interpretation of the recorded data during the compression test. The physiological shape was evaluated by a germination test. With increasing moisture content the seeds reacted as viscid bodies. Moist seeds were capable of more deformation and absorbed more energy until the tissue was ruptured. Dry seeds had a higher deformation resistance. The measured force, deformation and energy at the rupture point was significantly different between the tested varieties. The relationship between the applied energy and germination followed an optimum curve as germination decreased in the succession of 15.5, 17.5, 19.5, 13.5 and 11.5 % moisture content. Seeds with cracks in the embryo could have an intact testa and did not necessarily fail in germination. Only with dry seeds could all cracks be detected with the help of the force-deformation-curve of the compression test.

K e y w o r d s: pea seeds, moisture, quasi-static load

INTRODUCTION

During threshing and the following processing grains are subject to mechanical loading which can lead to mechanical damage and consequently to lower qualities of the harvested crop. If the grains are to be used for seed, they must be able to establish productive plants in the field. In this case quality is defined by the seed quality.

It is to be expected that pea seeds react very sensible to mechanical loading, as a seed consists to 90 % of an embryo and to 10 % of a thin testa. With any mechanical loading the embryo is always affected. Moreover the two relatively big cotyledons of the embryo are held together only with two small petioli and the testa.

The damaging effect of mechanical loading was already observed by Nobbe [11] in the early years of seed testing. Since then many researchers have focused on this topic [8,10,13,16]. Mainly mechanical loading during threshing and the following processing as transport was investigated. The knowledge of the mechanical loading capacity of a seed and the significance of mechanical damages on embryo and seedling growth improves the estimation of seed quality.

The objectives of this research were to estimate the mechanical loading capacity of pea seeds of different moisture contents and varieties under quasi-static load.

MATERIAL AND METHODS

Hand-harvested pea seeds (*Pisum sativum L.*) of three varieties, free of visible nontypic colours, pest infestation, sprouting, incomplete testa or undersize, were used for this study. The seeds were conditioned, and stored, in a controlled atmosphere at 5 °C over several months to 11.5, 13.5, 15.5, 17.5 and 19.5 % moisture content with a variance of the moisture content within each seed lot of $s^2 = 0.12\ \%^2$ [2]. For determining the moisture content an air-oven method (grinding, 130 °C for 1 h, wet mass basis) was used [5].

For uniaxial compression test a specially adapted universal instrument for strength testing from INSTRON model 4301 equipped with a 1 000 N load cell, parallel plates and a personal computer was used. A compression rate of 10 mm/min was adjusted. The force was obtained as an electric tension between 0 and 10 V each 10 ms. With a specially written computer programme the compression test for each individual seed could be stopped if an *a priori* desired value of energy, force or deformation was exceeded. The applied energy was calculated by an on-line integration of the force-deformation-curve [2].

All seeds were visually inspected after the compression test without using any auxiliary material. In some cases the testa was removed. The stressed seeds were conditioned to 15-18 % moisture content, treated with liquid Thiram and tested for germination following the ISTA-rules [5]. Deformations and cracks at the cotyledons as a result of the compression test were not evaluated as abnormal seedlings.

The deformation resistance was the force at a deformation of 0.07 mm. A peak in the force-deformation-relationship was detected when at an increasing deformation a decreasing force of at least 1 N was measured. The size of each seed was calculated with the help of the contact point between the loading tool and the seed. From time to time the masses of individual seeds were measured directly before the compression test.

For the study of the connection between a peak and the formation of a crack 1 000 seeds were compressed until a defined force was exceeded or a peak was determined. This defined force was adjusted to values between 50 and 1 000 N in steps of 50 N.

For comparison of some rheological properties under quasi-static load 100 single seeds of each variant were arranged in a complete randomised design. Germination tests were done with 2 replications with 100 seeds in a 3 factorial completely randomised block design. The factor energy had 6 levels with 0, 25, 50, 100, 200 and 400 mJ, the factor moisture content had 5 levels with 11.5, 13.5, 15.5, 17.5 and 19.5 % and the factor orientation had 2 levels with horizontal and vertical orientation (Fig. 1). Relative fre-

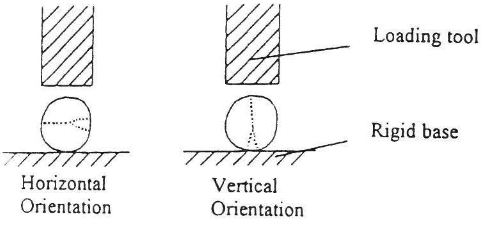

Fig. 1. Orientation of pea seeds in the universal instrument of strength testing.

quencies were arc-sin-transformed using the following formula [17]:

$$z(x) = \sqrt{n+1/2} \cdot \arcsin \sqrt{(x+3/8)/(n+3/4)}$$

where x is number of seeds with the mentioned expression and n - number of seeds per repetition.

For comparison of means the Tukey-test was applied. The regression analyses of linear regressions were calculated with the least square method [14]. Generally a significant level of $\alpha=0.05$ was used.

RESULTS

The force-deformation-curves had the characteristics shown in Fig. 2. The contact area between the seeds, the loading tool and the rigid base respectively increased during loading, because of the shape of the seeds. The seeds were of a more or less spherical shape, but with a large spread of variation within and between the varieties. The contact

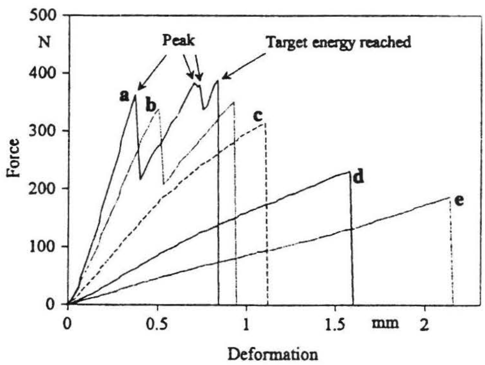

Fig. 2. Relationship between force and deformation of pea seeds for different moisture contents (a-11.5, b-13.5, c-15.5, d-17.5 and e-19.5 %) under quasi-static load up to an energy of 200 mJ was applied.

area between the seeds and the parallel plates depended on the orientation of the seeds during the compression tests. With increasing moisture content of the seeds smaller deformation resistances were measured (Table 1). With increasing moisture content the seeds reacted as viscid bodies. During compression numerous moist seeds were deformed without producing any crack in the embryo or testa. Only with seeds with a moisture content of 11.5 and 13.5 % in all cases cracks were observed and they appeared at the same time when peaks were determined. In many cases seeds with 15.5 to 19.5 %, cracks were observed although peaks were not measured. Therefore a peak as a criterion for the loading intensity could be used only for the seeds with 11.5 and 13.5 % moisture content.

The force-deformation-curves of seeds with 11.5 and 13.5 % moisture content had a linear characteristic with a mean correlation coefficient of r=0.99. Many force-deformation-curves of seeds with 15.5 to 19.5 % moisture content had a linear characteristic as well. If the seeds at which no peak could be measured were compressed until the maximum load of 1 000 N, a progressive characteristic of the force-deformation-curve was determined.

Depending on the variety, moisture content and orientation a significant different force, deformation and energy at the peak was determined (Tables 2 and 3). In Table 4 the coefficients of determination on the relationship between force, deformation as well as energy and deformation resistance, variety, mass as well as size of seeds with a moisture content of 13.5 % with the first crack under quasi-static load were shown.

The contact area was visible with all seeds by the visual examination. The first visually detectable cracks formed planes of refraction as meridian planes perpendicular to the parallel plates of the universal instrument of strength testing. A relationship between the moisture content or the orientation and the orientation of the planes of refraction was not observed. With dry seeds first

Table 1. Deformation resistance of seeds under quasi-static load depending on moisture content and orientation (LSD (α = 0.05) = 3.5)

Moisture content (%)	Deformation resistance (N)	
	Orientation	
	Horizontal	Vertical
11.5	50.3	44.3
13.5	36.9	34.3
15.5	19.2	22.8
17.5	10.2	15.4
19.5	7.3	8.4

Table 2. Rheological and physical properties of seeds with a moisture content of 13.5 % at the first crack under quasi-static load for different varieties

Resulting character	Variety			LSD (α=0.05)
	Belinda	Lisa	Solara	
Force (N)	347.5	301.4	360.8	22.1
Deformation (mm)	0.53	0.60	0.57	0.04
Energy (mJ)	97.2	96.4	109.2	10.1
Deformation resistance (N)	37.8	33.4	32.0	2.6
Mass (g)	0.234	0.205	0.289	0.013
Size (mm)	6.58	6.52	6.83	0.16

Table 3. Force, deformation and energy of pea seeds under quasi-static load at the first crack for different orientations and moisture contents

Resulting character	Orientation: Horizontal, Moisture content (%) 11.5	Horizontal 13.5	Vertical 11.5	Vertical 13.5	LSD (α=0.05)
Force (N)	409.4	329.2	322.0	354.0	30.1
Deformation (mm)	0.396	0.516	0.311	0.516	0.032
Energy (mJ)	79.7	88.2	48.5	94.8	9.6

Table 4. Coefficients of determination on the relationship between force, deformation as well as energy at the first crack and deformation resistance, variety, mass as well as size of seeds with a moisture content of 13.5 % under quasi-static load

Resulting character	Treatment factor	Partial coefficient of determination r^2	Total coefficient of determination r^2
Force	Deformation resistance	0.22	
	Mass	0.14	0.36*
Deformation	Mass	0.07	
	Variety	0.03	
	Size	0.02	0.12*
Energy	Size	0.08	
	Deformation resistance	0.06	
	Variety	0.03	0.17*

* significant at α = 0.05.

cracks were always observed in the embryo and then in the testa and with some seeds the testa stayed intact.

The germination percentage of seeds of the variety Belinda being stressed under quasi-static load depending on the applied energy, the moisture content and the orientation is shown in Fig. 3. The relationship between germination and moisture content followed an optimum-curve, as the average germination percentage of all levels of the factors energy and orientation decreased significantly in the succession of 15.5, 17.5, 19.5, 13.5 and 11.5 %. Hereby the germination percentage of seeds being stressed at 15.5 and 17.5 as well as 19.5 and 13.5 % moisture content at the horizontal and vertical orientation were not significantly different. The mean germination percentage of horizontally stressed seeds was significantly higher than the seeds being vertically stressed.

If an energy of at least 100, 200, 200 and 100 mJ was applied to the seeds with 13.5, 15.5, 17.5 and 19.5 % moisture content, respectively the germination percentage was significantly different to the control (0 mJ). In this case there were no significant differences between a horizontal and vertical orientation. In comparison hereto for seeds with a moisture content of 11.5 % at least 100 mJ at horizontal and 50 mJ at vertical orientation were necessary.

Mechanically damaged seeds formed typical abnormal seedlings. However, this could be observed with undamaged seeds as well. Seeds with cracks in the embryo could have

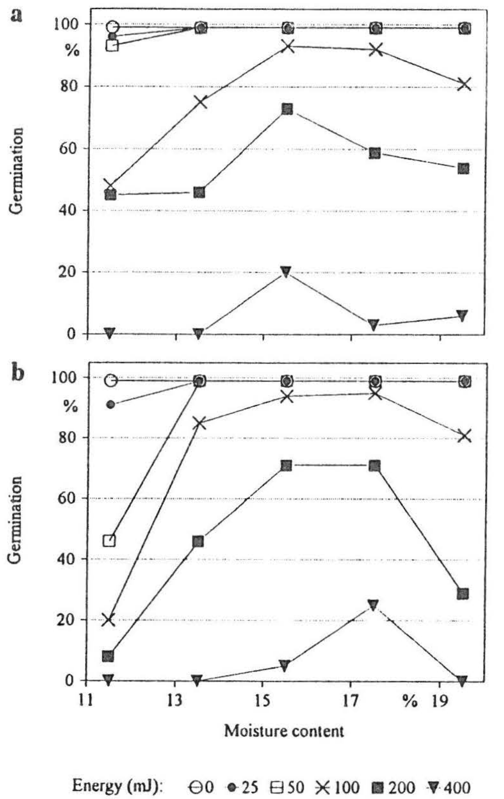

Fig. 3. Germination of quasi-statically loaded pea seeds for different applied energy, moisture content and horizontal (a) and vertical (b) orientations.

an intact testa and did not necessarily fail in germination. A crack was of more significance on germination than deformation.

DISCUSSION

Individual seeds in large numbers could be stressed under quasi-static load. The dependence of force, deformation and energy applied until a crack was detected, on the seed moisture content, orientation during compression and the variety could be measured for seeds with a maximum moisture content of 13.5 %. The relationship between the treatment factors deformation resistance, mass, size and variety could be estimated with a multiple linear regression with coefficients of determination of only 0.37, 0.11 and 0.18 (see Table 4). The resulting characters would have been estimated possibly much better by using more or other treatment factors. A consideration of the shape of the seeds could possibly contribute to a better estimation as the shape of the seeds influences the force-deformation-relationship.

A dependence on deformation resistance of the seeds and seed moisture content was detected. It was appropriate to use the deformation resistance as a measure of the viscoelastic behaviour of seeds at a deformation of 0.07 mm, as small irregularities, which can occur during the contact between seed and this loading tool, did not occur and peaks could not be detected up to this point [6,7].

It was not possible to detect any bioyield point or linear limit [9] for seeds of all moisture contents, as with many moist seeds, no peak in the force-deformation-curve was detected. The calculation of any modulus of elasticity (reviewed in [6]) therefore was not possible. Furthermore with increasing moisture content the possibility of detecting cracks in a seed during the compression test decreased. Paulsen [12] tested soybean seeds with moisture contents of up to 18 % and detected always a peak. However, he mentioned that the detection of peaks was more difficult with moist seeds. Other authors used the force and deformation at a peak of quasi-statically compressed seeds as well to determine the mechanical loading capacity [1,3,4,15,18]. A few of these investigations [1,4] were done with a maximum moisture content of 10 %. A damage analysis generally was not conducted.

CONCLUSIONS

1. With a force-deformation-relationship by itself, it was not possible to determine an appropriate mechanical loading capacity limit for seeds of all moisture contents.

2. An appropriate mechanical loading capacity limit for seeds of all moisture contents

may be found by stressing seeds up to a defined loading intensity and a following evaluation of the germination percentage.

3. The use of the applied energy as a measure for the loading intensity takes into account the relationship between moisture content and loading resistance.

4. Mechanically stressed seeds with a moisture content of 15.5 to 17.5 % had the largest germination percentage.

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