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DETERMINATION OF THE MECHANICAL PROPERTIES OF WINTER RAPE STALKS

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A b s t r a c t. The present study is concerned with determining the cutting energy in dynamic tests, and the bending stress, shearing stress, and cutting energy in static tests for stalks of winter rape of the Jupiter, Jantar, and Jet Neuf varieties. A considerable variability was observed in the mechanical parameters of winter rape stalks, along the length of the stalks as well as in the course of the phenological stages of the plants. The studies also showed differentiation between the varieties. The character of changes in the values of the mechanical parameters along the length of the stalk is described by square polynominals. An evaluation is made of the effect of the stalk cross section surface area and of the stalk density on the variability of the mechanical properties of winter rape stalks in the course of the development of the plants. It was found that the stalks of the Jupiter variety were characterized by the lowest density as compared to those of the Jantar and Jet Neuf varieties. Also, the spacing of plant rows and the number of plants per m^2 were found to have a significant effect on the variability of the mechanical properties of the stalks of the Jupiter variety.

INTRODUCTION

Studies on the mechanical properties of the stalks of winter rape are aimed at providing knowledge necessary for the evaluation of the susceptibility of the plants to lodging. As is commonly known, the phenomenon of plant lodging makes the process of harvesting difficult and has a negative effect on crop yields. The resistance of plants to lodging clearly depends on the mechanical properties of the stalks of individual plants. This fact has been reflected in the results of many years of research [1,2,3,4,5].

The present study is concerned with determining the cutting energy in dynamic tests, and the bending stress, shearing stress, and cutting energy in static tests. These parameters are used to characterize the mechanical properties of winter rape stalks. Also, an evaluation is made of the effect of the stalk cross section surface area and of the stalk density on the variability of the mechanical properties of winter rape stalks in the course of the development of the plants.

MATERIALS AND METHODS

The studies were conducted using stalks of winter rape from varietal and agrotechnical experiments located at the Zadąbrowie Experimental Station.

- Varietal experiments - measurements were taken during the vegetation of the plants (at full silique filling and at technical and full ripeness) of the Jupiter, Jantar, and Jet Neuf varieties.
- Agrotechnical experiments - measurements were taken on stalks of the Jupiter variety during the vegetation of the plants. The experiment comprised three different sowing densities: W_1=120 seeds/m^2, W_2= =240 seeds/m^2, W_4=480 seeds/m^2, and two values of drill spacing: R_1=15 cm, and R_4=45 cm. After the winter period the following numbers of plants remained in the particular combinations of the experiment: R_1W_1 - 48 plants/m^2,

R_1W_2 - 54 plants/m^2,
R_1W_4 - 126 plants/m^2,
R_4W_1 - 43 plants/m^2,
R_4W_2 - 53 plants/m^2,
R_4W_4 - 72 plants/m^2.

Measurements were performed on 30 stalks representative of a given variety. Then, after cutting off the siliques and the offshoots, the stalks were divided into six successive sections (counting from the root), after which five successive sections of the stalks were used for the determination of the mechanical parameters in order to identify their variability along the stalk of the plant. Rape stalks from the agrotechnical experiment were studied up to the middle of their height (the lower half of the stalk), and in this case measurements were taken at three points on the stalk. The strength characterization of the rape stalks was obtained by determining the shearing energy (Ed) in a dynamic test. The value of the shearing energy was measured by means of a Dynastat apparatus operating on the principle of a pendulum hammer moving at a speed of v=2.1 m/sec. In the static tests, an Instron apparatus was used to determine, in the process of bending, the maximum bending stress (σ_{max}), and, in the process of shearing, the shearing energy (Ed) and the maximum shearing stress (τ_m). The results of the determinations were recorded by means of a computer system, using software designed especially for the purpose. In the static tests the process of shearing was effected by means of special cutting tools causing simultaneous shearing of the double surface of the stalk. The shearing energy (Es) in the test was obtained by integrating the curve plotted by means of the static shearing force. The values of Ed and Es were used to calculate the values corresponding to the work required to shear a unit of stalk cross section surface area (Wd and Ws). The shearing stress was expressed by the relation

$$\tau_{max} = \frac{P'_{max}}{2S} \qquad (1)$$

where P'_{max} - maximum shearing force, S--stalk cross section surface area.

The maximum bending stress was obtained from the formula

$$\sigma_{max} = P_{max} l \qquad (2)$$

where P_{max} - maximum bending force, l-length of stalk section subjected to bending - 7 cm

This formula was determined for a circular stalk cross section, completely filled, from the expression $\sigma_{max}=Mg/W$, while the diameter was evaluated through stalk cross section surface area [1].

The natural stalk cross section S and the stalk cross section after removal of the parenchyma S' were measured by means of ΔT of a British-made aerometer. Also, the densities ρ and ρ' of stalk sections 3 cm long were determined by the geometrical method acc. to the formula

$$\rho = \frac{M}{lS}; \qquad \rho' = \frac{M}{lS'} \qquad (3,4)$$

where M-mass of a stalk section 3 cm long, l-length of the stalk section tested, S-natural cross section of the stalk, S'-cross section of the stalk after removal of the parenchyma.

Also, the content of skeletal substances (lignin, cellulose, and hemicellulose) was determined for three varieties of winter rape at three phenological phases of the plants according to methods of Ślusarczyk [6].

RESULTS AND DISCUSSION

The investigations have allowed for a broad characterization of the strength parameters of the rape varieties under study, eg. for Jupiter, and for an assessment of the effect of the cross section area, density, and content of skeletal substances on the variability of the strength properties of rape stalks. The study has shown the existence of inter-varietal differences. All of the parameters studied were characterized by a considerable variability along the stalk

length as well as in the course of the plant growth and development (Fig. 1)

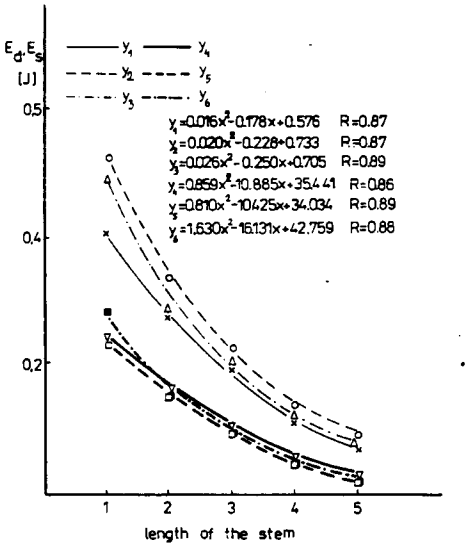

Fig. 1. Distribution of the values of the shearing energy in dynamic and static tests along the stem of Jupiter rape in successive phenophases (x, o, Δ, ∇, □, ■-experimental points, y_1..., y_6-regression curve, xy_1; ∇y_4-complete silique filling, oy_2; □y_5-technical ripeness, Δy_3; ■y_6 - full ripeness).

It was found that the shearing energy determined in both types of tests, i.e. static and dynamic, had similar variabilities both as concerns varieties and in the course of the plant growth (high positive correlation - Es x Ed: for Jupiter r=0.91 at siliques filled, r=0.95 at technical ripeness, and r=0.93 at full ripeness; for Jantar r=0.90 at siliques filled, r=0.93 at technical ripeness, and r=0.90 at full ripeness), although the orders of magnitude of the energy values were different. It was found that distinctly lower values of shearing energy characterized the stalks of Jupiter as compared to those of Jantar and Jet Neuf, their values falling into corresponding ranges: Ed-Jupiter 0.10 to 0.53 J, Jantar 0.11 to 0.60 J, Jet Neuf 0.11 to 0.55 J; Es-Jupiter 0.02 to 0.29 J, Jantar 0.03 to 0.31 J, and Jet Neuf 0.03 to 0.35 J. It was established that the character of changes in the shearing energy values along the length of the stalk is described by a square polynomial. The study showed that the variability of the value of energy required to shear the stalk is strongly affected by the value and character of changes in the cross section area (S), cross section area of stalk with the parenchyma removed (S'), and stalk density (ρ). A strong relation between Es and S,S', and between Ed and S,S' (high correlation coefficients) was noted for all the varieties studied (for Jupiter r=0.70-0.91, r=0.72-0.90, and r=0.67-0.95, r=0.69-0.95; for Jantar r=0.54-0.88, r=0.61-0.87, and r=0.49-0.91, r=0.61-0.90; for Jet Neuf r=0.93-0.94, r=0.92-0.93, and r=0.77-0.93, r=0.77-0.92). A weaker significant correlation between Es and ρ, ρ', and between Ed and ρ, ρ' was also found (for Jupiter r=0.29-0.55, 0.25-0.49 and r=0.25--0.50, 0.20-0.45; for Jantar r=0.64-0.84, 0.67-0.84 and r=0.62-0.82, r=0.66-0.79; for Jet Neuf r=0.23-0.78, 0.20-0.78 and r=0.28-0.70, 0.23-0.67).

The study showed varietal differences. At the same time, it was found that the value of shearing energy per unit of stalk cross section area (Wd, Ws) showed varietal differentiation, along with differentiation in the values of the parameters under study in the course of the phenological stages of the plants (Fig. 2). The shearing energy (Wd) in the dynamic tests on the Jupiter variety showed a non-linear character of variability on the length of the stalk, with a minimum observed at the second or third sections tested. The shearing energy (Ws) in the static test, on the other hand, did not support such a characterization of the variability. This relation did not occur with the other varieties, although it had already been known from earlier studies (Skubisz *et al.*, 1988), and it is related to the content of the parenchyma which varies on the stalk length as if it were the factor determining the parabolic character of the changes in the mechanical parameters. It was also found that the Jupiter variety is charac-

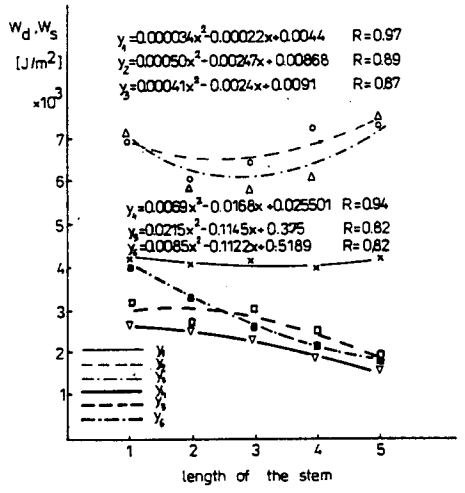

Fig. 2. Distribution of the values of the shearing energy per stem cross-section area unit in dynamic and static tests along the stem of Jupiter rape in successive phenophases, explanations as Fig. 1.

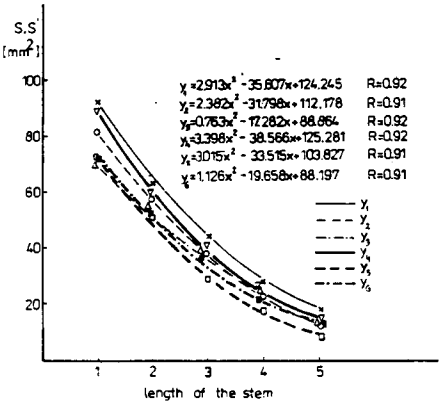

Fig. 3. Distribution of the values of the cross-section area unit along the stem of Jupiter rape in successive phenophases, explanations as Fig. 1.

terized by the highest values of Wd and Ws which formed the following ranges: Jupiter 3990-7511 J/m^2 and 1521-4156 J/m^2, Jantar 3903-7496 J/m^2 and 805-4033 J/m^2, and Jet Neuf 4462-6516 J/m^2 and 874-3660 J/m^2. An analysis of the variability of the parameters under study in the course of the plant development showed that the shearing energy values (Wd and Ws) reached their maximum values during technical ripeness. It was found that the variability of the values of shearing energy per m^2 is characterized by a square polynomial. A statistical analysis of the results obtained showed that such parameters as S, S' and ρ, ρ' did not have a highly significant effect on the variability of Wd and Ws (Fig. 3). The coefficients of correlation between W_d and S,S', and between W_s and S,S' were insignificant (Jupiter r=0.04-0.37, Jantar r=0.01-0.25, and Jet Neuf r=0.13-0.65).

The stalks of the Jupiter variety were found to be characterized by the lowest values of cross section area (S and S') which formed, respectively, the following ranges: Jupiter - 13.1-90.9 mm^2 and 11.4-90.6 mm^2, Jantar - 15.0-94.7 mm^2 and 14.0-92.8 mm^2, and Jet Neuf - 17.9-96.7 mm^2 and 15.4-95.9 mm^2, and had the lowest density: Jupiter - -189-798 kg m^{-3}, Jantar - 326-864 kg m^{-3} and Jet Neuf - 331-879 kg m^{-3}. With all the varieties the stalk density reached its minimum values during full ripeness.

An assessment of the content of skeletal substances in rape stalks showed that there is a close relationship between the variability of the mechanical properties of the stalks of the varieties under study and the content of lignin, cellulose, and hemicellulose. It was found that Jupiter had twice the content of lignin (Jupiter 13.6--27.9%, Jantar 11.0-17.9%, Jet Neuf 7.0--15.5%) and half the content of cellulose (Jupiter 7.2-16.9%, Jantar 24.7-32.6%, Jet Neuf 15.0-29.9%) as compared to the Jantar and Jet Neuf varieties. On the other hand, there were no significant differences between the varieties in their content of hemicellulose (Jupiter 7.3-15.5%, Jantar 12.6-14.9%, Jet Neuf 8.0-15.3%).

The shearing stress (τ_m), (Fig. 4) in turn, showed a very close relationship with the stalk cross section area (S) and with the stalk cross section area after removal of the parenchyma (S'), the correlation coefficients falling within the following ranges of

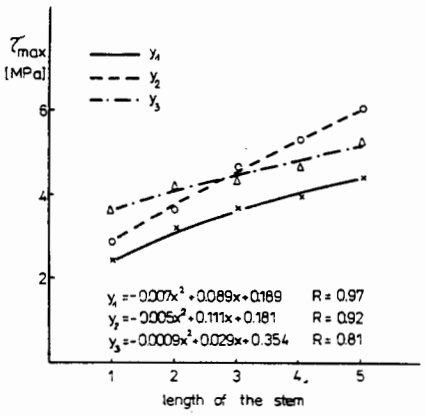

Fig. 4. Distribution of the values of the shearing stress along the stem of Jupiter rape in successive phenophases (x, o, Δ -experimental points, y_1, y_2, y_3-regression curve, xy_1-complete silique filling, oy_2-technical ripeness, Δy_3-full ripeness).

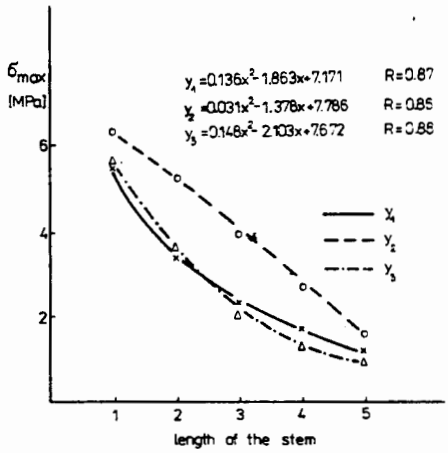

Fig. 5. Distribution of the values of the bending stress along the stem of Jupiter rape in successive phenophases, explanations as Fig. 4.

values: Jupiter - r=-0.52 to 0.59 and r= =-0.48 to 0.60, Jantar - r=-0.59 to 0.73 and r=-0.54 to 0.73, Jet Neuf - r=-0.62 to 0.72 and r=-0.62 to 0.69. On the other hand, no close relationship was found between the shearing stress and the stalk density, the correlation coefficients obtained being fairly low to insignificant. The character of the shearing stress variability on the length of the stalk is described by a square polynomial.

It was also found that the variability of the stalk bending stress (σ_m), on the length of the stalk as well as in the course of the plant development, was significantly correlated to the stalk density. (Fig. 5,6). A significant correlation between the variability of the stalk bending stress and the stalk density was obtained for the Jantar and Jet Neuf varieties, while the Jupiter variety was characterized by considerably lower coefficients of correlation between the parameters under analysis - σ_m, x, ρ, ρ': Jupiter - -r=0.19-0.69 and r=0.28-0.74, Jantar - -r=0.33-0.69 and r=0.49-0.81, and Jet Neuf - r=0.62-0.77 and r=0.65-0.98.

Therefore, a strong relationship was determined between the variability of the mechanical properties of stalks and their structure as expressed by means of the cross section area (S, S'), the density (ρ, ρ'), and the content of lignin, cellulose, and hemicellulose.

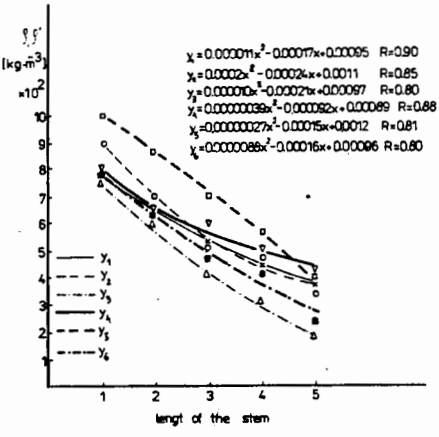

Fig. 6. Distribution of the values of the density along the stem of Jupiter in successive phenophases, explanations as Fig. 1.

A study of the mechanical properties of rape stalks of the Jupiter variety from the agrotechnical experiment confirmed the effect of row spacing and of the number of plants per m^2 on the variability of the mechanical parameters of the stalks (Fig. 7,8). It was found that the values of the stalk shearing energy (Ed and Es) are higher for plant row spacing of 45 cm compared to the value of energy necessary to shear a stalk from a plot where the plant row spacing was 15 cm. Both types of study identically characterize the physical properties of stalks of plants from the R_1 and R_4 experiments.

Considering the effect of the number of plants per m^2 on the mechanical properties

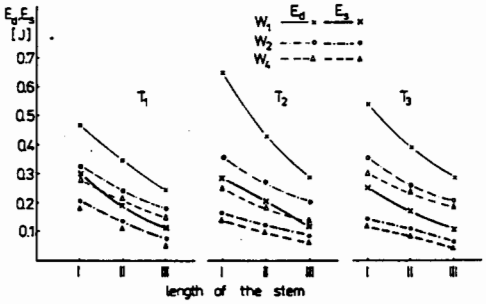

Fig. 7. Distribution of the values of the shearing energy along the stem of Jupiter rape in the agrotechnical experiment during rape vegetation, and row spacing R_1=15 cm (x,y-Ed and Es for W_1=120 seeds per m^2, o,•-Ed and Es for W_2=240 seeds per m^2, Δ,▲-Ed and Es for W_4=480 seeds per m^2).

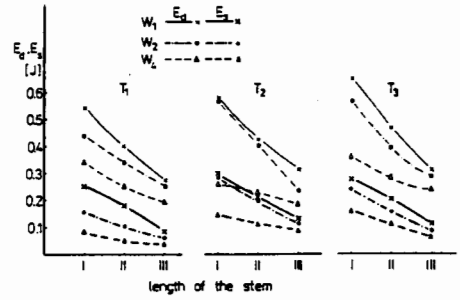

Fig. 8. Distribution of the values of the shearing energy along the stem of Jupiter rape in the agrotechnical experiment during rape vegetation, and row spacing R_4=45 cm, explanations as Fig. 7.

of rape stalks of the Jupiter variety, it was determined that the stalks of plants from the highest sowing density, W_4, were characterized by the lowest values of stalk shearing energy. This observation was true irrespective of the plant row spacing. However, the results of determinations of the mechanical properties of rape stalks from the agrotechnical experiment were more consistent when obtained from dynamic rather than static tests.

It was found that the stalks of plants grown at row spacing R_1=15 cm contained somewhat less hemicellulose (12.3-15.1%) compared to those from R_4=45 cm (14.6-16.4%). High density of plants had no significant effect on the percentage content of hemicellulose in the stalks, and even resulted in a lowering in its value at the end of ripening.

The stalks of the Jupiter variety had a very high content of cellulose, the percentage value of which at the narrow row spacing (15 cm) was only slightly higher (28.7-33.6%) than at the broad spacing (45 cm- 24.6-31.2%). As the plant density increased, especially in combination with the narrow row spacing, the content of cellulose in the stalks decreased slightly, while with the broad spacing its value was more stable, decreasing with the ripening of the plants. Analyzing the percentage content of lignin in the stalks of the Jupiter variety it was found that it was comparable to the content of hemicellulose, with higher values (10.6--15.3%) at narrow plant row spacing (15 cm) than at broad plant row spacing (45 cm - -11.8-13.5%). In plots where the extreme sowing densitites had been applied, a high stability of the lignin content was observed in the course of the plant development. With medium sowing density, the stalks had the highest lignin content in the case of the narrow plant row spacing (15 cm). It was established, therefore, that plants grown in plots with narrow row spacing were significantly more responsive to plant density, which was evident from the skeletal struc-

ture of their stalks, and contained more lignin and cellulose.

CONCLUSIONS

1. A considerable variability was observed in the mechanical parameters of winter rape stalks, along the length of the stalks as well as in the course of the phenological stages of the plants. The studies also showed differentiation between the varieties.

2. The character of changes in the values of the mechanical parameters, cross section area, and density along the length of the stalk was described by square polynomials.

3. The shearing energy per unit of cross section area, determined in dynamic tests (Wd), reached its minimum value in the second or third test section. No effect of the variability of cross section area S,S' on the values of the shearing energy Wd and Ws was observed. At the same time a significant correlation between the variability of these parameters and the stalk density (ρ and ρ') was observed during the technical and full ripeness of the plants.

4. It was found that the stalks of the Jupiter variety were characterized by the lowest density compared to those of the Jantar and Jet Neuf varieties.

5. The shearing stress (τ_m) was correlated in an inverse proportion with the cross section area of the Jupiter variety in all the phenological phases, while in the case of the Jantar and Jet Neuf varieties no such relationship existed during full ripeness. The density of the stalks had no significant effect on the variability of the shearing stress.

6. The bending stress (σ_m) showed a significant relationship between its variability and the value of the cross section area (S, S') and of the stalk density (ρ, ρ'). It was found that the lowest coefficients of correlation of this parameter and stalk density occurred in the case of the Jupiter variety.

7. The spacing of plant rows and the number of plants per m^2 were found to have a significant effect on the variability of the mechanical properties of the stalks of the Jupiter variety.

8. It was found that the stalks of plants from the plots with the highest sowing density were characterized by the lowest values of shearing energy, irrespective of the plant row spacing.

9. It was found that plants from the plots with narrow plant row spacing showed a significant response to sowing density, as evidenced in the structure of their stalks, and contained more lignin and celluloses.

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OKREŚLENIE WŁAŚCIWOŚCI MECHANICZNYCH RZEPAKU OZIMEGO

W niniejszej pracy określano energię cięcia w badaniach dynamicznych oraz naprężenie zginające, ścinające i energię cięcia w badaniach statycznych dla łodyg rzepaku ozimego odmiany Jupiter, Jantar i Jet Neuf. Stwierdzono dużą zmienność parametrów mechanicznych łodyg rzepaku ozimego zarówno wzdłuż łodygi jak i w fazach fenologicznych. Badania wykazały zróżnicowanie międzyodmianowe. Charakter zmian wartości parametrów mechanicznych wzdłuż łodygi opisuje wielomian 2-ego stopnia. Ponadto dokonano oceny wpływu powierzchni przekroju poprzecznego łodygi i gęstości na zmienność właściwości mechanicznych łodyg analizowanych odmian rzepaku ozimego w czasie rozwoju rośliny. Stwierdzono, że łodygi odmiany Jupiter charakteryzowały się najmniejszą gęstością w porównaniu z odmianą Jantar i Jet Neuf. Jednocześnie stwierdzono istotny wpływ rozstawy rzędów oraz obsady roślin/m^2 na zmienność właściwości mechanicznych łodyg odmiany Jupiter.