JOURNAL OF MATERIALS SCIENCE 23 (1988) 3588-3593

Mechanical properties of some plant materials

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A study of mechanical properties of some plant materials, particularly vegetable flesh and cultural plant stalks is reported. It is shown that the tensile (compressive) strength, σ_m, of these and other plant materials is controlled by a relatively close exponential regression relation $\sigma_m = 0.2E^{0.75}$, where E is Young's modulus ($r = 0.975$). More significant deviations from this relation are explained by the participation of buckling strength in the deformation by compression of the materials consisting of large thin-walled cells filled with air. A marked dependence of Young's modulus and strength of plant tissues on the crude fibre content is also demonstrated.

1. Introduction

Plant tissues of various origin are characterized by markedly different mechanical properties. For this reason we can encounter, on the one hand, soft and juicy fruits and, on the other, strong fibres or strong, tough woods. The variability of the mechanical properties of plant products is enormous [1] and it is of great importance both for the existence of the plants themselves and for the technology of their cultivation and utilization of plant products in agriculture and industry.

This paper presents measured values of Young's modulus, tensile (compressive) strength and shear strength of several agricultural products and discusses the relations between the measured values and between these quantities and the crude fibre content in the products tested.

2. Experimental procedure

Tests were made of rye straw and fleshy parts of vegetables supplied for experiments by various breeding institutes in Czechoslovakia at the time of their harvest. The characteristics of the materials used are given in Table I. Some data in this table refer to several sets: under the heading of "rye straw" there are several measurement sets to various parts of the straw, other cases involve several measurement sets from various years, etc. In the case of lucerne stalks, several measurement sets relate to various phases of growth of the plant. The number of repeated measurements within the framework of a measurement set was about 20 in the majority of cases, and was never lower than 10.

The specimen deformation was produced by Instron deformation machines, mostly of the 1122 type, with a constant deformation rate. Tensile tests were carried out on specimens with an active length of 25 mm, consisting, in the case of stalks and straws, of segments 2 to 4 mm wide, in the case of skins, of strips 5 mm wide, and in the case of fleshy samples of special shapes, of parts for testing which had a 5 mm × 5 mm cross-section. Young's modulus of lucerne stalks was obtained from the bending test. The compression test of the flesh was made using cylinders, 15 mm diameter and 23 mm long, cut from the centres of fleshy products. Only tomato flesh is an exception, the sample length of which was determiend by the thickness of the outer pericarp of the fruits. The shearing test of stalks was made in a special jig enabling double shearing of the stalk in two parallel planes perpendicular to the stalk axis. The fleshy samples were tested analogously; for this purpose cylinders, 10 mm diameter, were cut out of the flesh.

The deformation rate was approximately 0.1 mm sec^{-1} (0.0833 to 0.167 mm sec^{-1}) in the majority of cases. The only exception was the deformation of the rye straw in tension where a deformation rate of 0.0167 mm sec^{-1} was used.

The values of Young's modulus were obtained from the deformation curves obtained from tensile, compressive and bending deformation tests by the usual methods (see e.g. [1]). The shear strength values were calculated from the maximum shear forces attained in the course of the tests [1]. Also, the calculation of the tensile and compressive strengths was based on the maximum values of the respective deformation curves; corrections were made, however, for the changes of the sample cross-sections in the course of the tests. The corrections were based on the assumption that the tested material was incompressible. For tensile deformation this procedure is expressed by the relation for the strength, σ_m,

$$\sigma_m = \frac{F_{max}}{S}(1 + \varepsilon) \quad (1)$$

where F_{max} is the force corresponding to the state in which the rupture of the sample took place, S is the initial cross-section of the sample, and ε is the strain of the sample at the moment of its rupture

$$\varepsilon = \frac{l - l_0}{l_0} \quad (2)$$

where l_0 is the initial sample length and l is its length at the moment of rupture. The same Equations 1 and

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TABLE I Experimental material

Plant	Part	Variety	Year	Dry matter content (%)	Crude fibre content (%)	Set number
Rye	stem	Kustro	1981	92 ± 0.5	55 ± 1.2	1
Lucerne	stem	Palava	1979	22.8	5.4	2
				24.4	7.0	3
				27.3	10.9	4
				34.1	14.3	5
Tomatoes	fruit flesh	Intermech	1976/77	~5	–	6
	outer	Nova				7
	pericarp	Nuova AT 30				8
		Vrbičanské				9
		Tanzimech				10
	fruit skin	Intermech	1976/77			11
		Nuova AT 30				12
		Vrbičanské				13
		Tanzimech				14
Potatoes	central parts	Boubín	1981–83	23.1–28.2	0.35–0.65	15
	of tubers	Karin	1981–83	17.9–19.5	0.25–0.38	16
		Oreb	1983	29.1	0.35	17
		Ostara	1985	18.5	0.28	18
		Resy	1981–85	15.9–18.4	0.26–0.43	19
Radish	central parts	Duo	1983	3.0	0.01	20
	of roots	Saxa	1981–83	3.0–4.7	0.012–0.036	21
		Slavie	1983	4.0	0.04	22
Carrot	central parts	Chantenay	1981/82	9.7–15.4	0.46–0.60	23
	of roots	Karotina	1982/83	14.4–19.3	0.99–1.0	24
		Larossa	1981	12.0	0.73	25
		Nantézská	1983	16.0	0.75	26
		Rubína	1983	22.7	1.13	27
Kohlrabi	central parts of roots	Gigant	1981/82	7.4–15.9	0.28–0.55	28
Red beet	central parts	Betina	1981–83	16.0–25.0	0.80–1.18	29
	of roots	Červená Kulatá	1983	16.0–20.0	0.71–0.87	30

2 can be used for compressive deformation; however, the strain attains negative values in this case. If we interpret the strength by expressing the component of the stress tensor which loads the sample in the condition in which it loses its stability then, according to the standard sign convention, σ_m must also take negative values for compressive deformation. This is achieved by substituting for F_{max} in Equation 1, the value of which is negative under this sign convention. However, the compressive strength is generally given in the form of the absolute value of the respective stress; in our paper we will use this presentation method, too.

3. Results and discussion

The measured mean values of Young's modulus as well as the values of the tensile, compressive and shear strengths are given in Table II. Further statistical data are not incorporated into the table because of the diverse structure of the sample sets investigated, differing in the number of test repetitions and the degree of detail of description given in Table I, in which some data conceal information on several sets. Briefly, however, it is possible to say that the variation coefficients amounted to 15 to 30% for Young's modulus, 10 to 20% for tensile and compressive strengths, and 5 to 15% for shear strength.

The strength and Young's modulus are cross-correlated, as shown in Fig. 1. The data from Table II were supplemented in this figure with the data obtained from the literature. Fig. 1 shows that the relation between the tensile (compressive) strength and Young's modulus can be expressed as

$$\sigma_m = aE^n \quad (3)$$

where the exponent $n \approx 0.75$ and a is a material parameter. All measurements shown in Fig. 1 can be expressed by a single relation with the exception of balsa which has markedly lower strength values than those characterized by the regression relation obtained for other plant parts tested. The relation between strength and Young's modulus of balsa can be described by a special equation which, however, also has an exponent of $n \approx 0.7$. The cause of the different character of the σ_m–E relation must be sought in the cellular structure of the balsa. The relatively large, air-filled cells collapse under pressure due to the loss of stability in buckling [9] at lower macroscopic stresses than those required for failure of the cell walls due to "pure" tensile or compressive stresses. All other deformed materials in Fig. 1 consist of cells filled with a liquid or starch (endosperm), or are deformed by tension; in all of these cases the buckling strength does not come into consideration.

TABLE II The results obtained

Set number*	Young's modulus (MPa)		Strength, σ_m (MPa)		
	Tension	Compression	Tension	Compression	Shear
1	3000–7000	–	55–120	–	–
2	981†	–	–	–	6.1
3	1880†	–	–	–	7.5
4	2800†	–	–	–	11.5
5	3250†	–	–	–	9.3
6	–	0.33	–	0.094	–
7	–	0.55	–	0.140	–
8	–	0.75	–	0.240	–
9	–	0.35	–	0.110	–
10	–	0.36	–	0.120	–
11	26.4	–	2.55	–	–
12	23.3	–	2.16	–	–
13	70.2	–	5.67	–	–
14	28.1	–	2.47	–	–
15	–	3.27–5.39	–	0.95–1.18	0.456–0.569
16	–	3.38–7.24	–	0.88–0.96	0.434–0.444
17	–	4.07	–	0.97	0.539
18	2.78	3.18	0.754	0.93	0.376
19	4.21	3.14–5.14	0.716	0.83–0.97	0.435–0.469
20	–	2.72	–	0.37	0.191
21	–	2.28–3.26	–	0.68–0.70	0.219–0.379
22	–	–	–	–	0.314
23	–	6.23	–	1.55	0.567–0.696
24	–	7.83	–	1.94	0.896–0.949
25	–	–	–	–	0.942
26	–	5.07	–	1.66	0.870
27	–	–	–	–	0.951
28	–	6.50–6.70	–	1.61–1.68	0.74–0.75
29	–	4.80–5.35	–	1.52–1.66	0.619–0.881
30	–	–	–	–	0.760–0.820

*See Table I.
†Results obtained in bending tests (three-point bending tests; the distance between the both supporting points was ≈ 40 mm).

Fig. 1 shows also that the scatter of experimental values with reference to the principal regression relation is not the same over its whole range. The regression analysis of partial subsets (Fig. 2, Table II) shows that in several cases (1b, c, e) the regression exponential relation approaches the linear relation ($n \approx 1$) with values of the parameter a within the limits of 0.01 and 0.1. If a general linear relation is used, acceptable results are obtained even for the vegetable flesh ($r = 0.960$ [10]). Various linear relations approximating experimental values of partial subsets express the specific properties of the individual plant materials as a possible source of the observed heterogeneity of the observed scatter in the σ_m–E relation. Another significant source of this scatter is the marked variability of Young's modulus, strongly dependent on deformation conditions and details of the structure of materials; they include, in particular, the water content of the

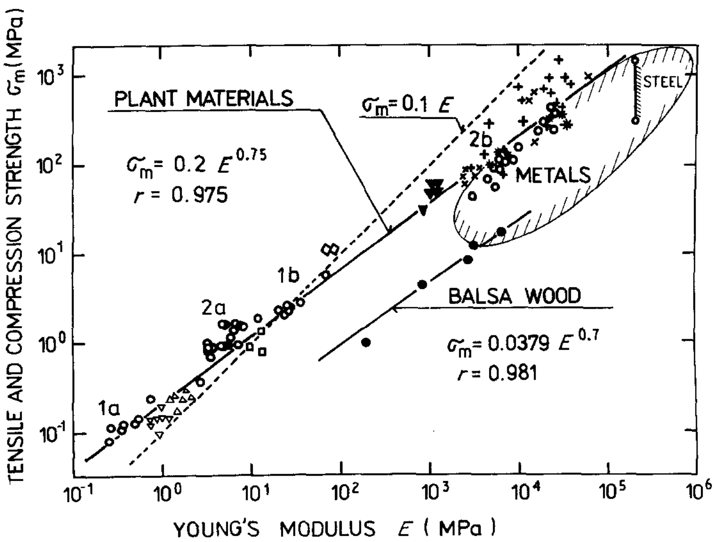

Figure 1 Relation between strength and Young's modulus of plant materials. (○) 1a, tomato flesh (items 6 to 10 in Table I); 1b, tomato skin (items 11 to 14 in Table I); 2a, vegetable flesh (items 15 to 30 in Table I); 2b, straw stalks (item 1 in Table I). (+) plant fibres – tension [2]. (×) plant fibres – tension [3]. (∗) Sclerenchyma and colenchyma of plants – tension [4]. (▼) Endosperm of cereals – compression [5]. (▽) Melon flesh – compression [6]. (△) Apple flesh – compression [6]. (◇) Tomato skin – tension [7]. (□) Apple skin – tension [8]. (●) Balsa – compression [9]. The regression relations shown in the figure are the numerical expression of relations between σ_m and E given in MPa.

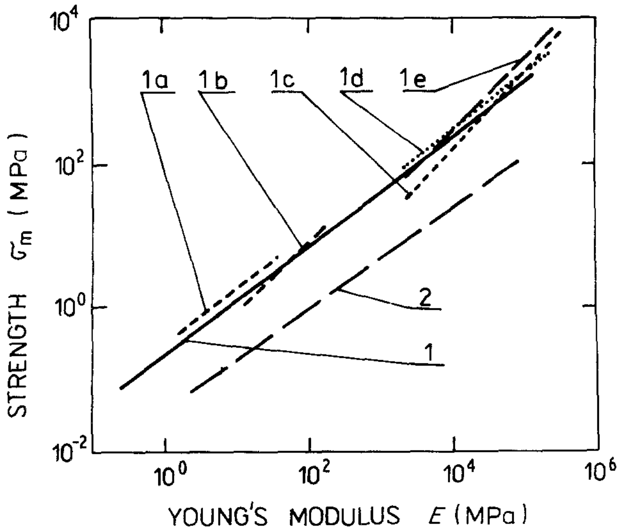

Figure 2 Regression relations between tensile compressive strength and Young's modulus. Line 2 refers to balsa (Fig. 1), line 1 to the relation $\sigma_m = 0.2E^{0.75}$ from Fig. 1. Other lines (1a to 1e) refer to partial subsets – see Table III.

material [10, 11], the degree of organization of cellulose and its content of the crystalline phase [2, 3], and the deformation mechanism of the material [6, 9, 12], etc.

The dotted line in Fig. 1 shows the relation of $\sigma_m = 0.1E$ which represents the simplest expression of the theoretical strength of crystalline materials [13]. According to this figure the experimental values of σ_m are lower than $0.1E$ for the plant materials with Young's modulus higher than $\simeq 20$ MPa, while in the case of the materials with Young's modulus lower than $\simeq 20$ MPa the situation is exactly the opposite. In the proximity of the above boundary of $E \approx 20$ MPa in Fig. 1, experimental values are obtained from the fruit skins which are the very material for which the exponential regression relation (Table II, 1b) was found to approach the linear relation ($n = 0.849$) with the value of $a = 0.102$ to ~ 0.1. Consequently, the relation $\sigma_m = 0.1E$ is expressed very well by the experimental values for fruit skins. Stronger and tougher plant materials than the skins, therefore, must be characterized by lower values of parameter a in Equation 3 applied to a partial subset, and it was shown that it was possible to approximate less strong materials than the fruit skins by the exponential Equation 3 with the values of parameter a higher than 0.1. These conclusions fully agree with the values of parameter a given in Table III.

Fig. 1 also shows the region of experimental values of σ_m and E for technical metals and separately for steel. According to this figure, plant fibres have a higher strength than some metals and are comparable in this respect even with steel. The high strength of plant fibres stands out particularly if compared with the strength of metals with the same value of Young's modulus. This is also testified to by the high values of parameter a from Equation 3 used to approximate the experimental data for plant fibres (see Table III, 1c, 1d, 1e); in general, these values are higher than the usual values of the ratio of σ_m/E for technical materials (0.001 to 0.02 [13]).

TABLE III Parameters of the regression Equation 3 for the values of quantities σ_m and E from Table II and Fig. 2 (given in MPa)

Data set		a	n	r
1	All data from Fig. 1 except for balsa	0.200	0.750	0.975
1a	Vegetable flesh, items 15 to 30 from Table II	0.325	0.769	0.713
1b	Apple and tomato skins, items 11 to 14 from Table II [8]	0.102	0.949	0.970
1c	Straw stalks, item 1 from Table II	0.010	1.044	0.877
1d	Plant fibres [2]	0.203	0.790	0.817
1e	Plant fibres [5]	0.031	0.989	0.890
2	Balsa [9]	0.038	0.700	0.981

Adherence to the linear relation between strength and Young's modulus of the individual plant materials, while simultaneously preserving the exponential Equation 3 with the values of the parameters $a = 0.2$ and $n = 0.75$ for a wider set of materials, means that the decrease of Young's modulus must be followed by an increase of the σ_m/E ratio as well as the value of parameter a for the partial subsets. In practice, this means that with the decreasing value of Young's modulus the plant material becomes more deformable and the loss of its strength takes place under higher deformations.

The cell walls with cellulose as their principal component represent the basic load-bearing elements of plant tissues. Therefore, it can be assumed that the volume representation of cell walls in the tissue represents the measure of its strength. In the analyses of composition of plant materials the main part of the cell wall building materials is characterized as crude fibres, the weight concentration of which in the samples (c_v) is shown in Table I. The volume representation of crude fibre content, c'_v, in the sample can be expressed by the relation

$$c'_v = c_v \varrho / \varrho_c \tag{4}$$

where ϱ is the mean density of the tested material and ϱ_c is the mean density of the crude fibres. The density of the crude fibres is not a "well-defined" quantity; however, it can be assessed by an approximate value of 1500 kg m^{-3} [9].

The numerical differences between the quantities c_v and c'_v are particularly high in the case of dry materials, where the ϱ/ϱ_c ratio drops to values of $\simeq 0.2$, while in the case of vegetable flesh it varies between 0.6 and 0.7. Reliable densities, ϱ, could be found only for some cases of tested materials and some cases adopted from the literature; in these instances the values of c'_v in the samples were determined by means of Equation 4. This was possible in the case of stalks and some plant fibres [3, 15]. Reliable data on the density of tested material are not available for flesh. The representation of the crude fibre content in tested materials, therefore, was characterized by the quantity denoted as c_v^+ which is expressed by means of the weight representation, c_v, in the case of fleshy produce and by the volume representation, c'_v, in the case of plant stalks and plant fibres.

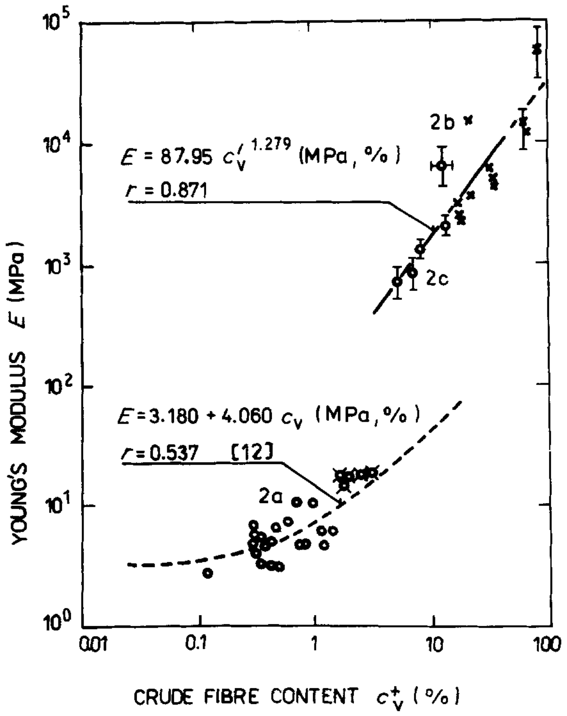

Figure 3 Young's modulus of plant materials plotted against the crude fibre content of the material. In the case of dry materials, c_v^+ signifies the volume representation of the crude fibres in the sample (for details see text). (○) Present study: 2a, vegetable flesh; 2b, dry rye straw stems; 2c, lucerne stalks. (⊹) Sweet potato tubers [14]; (x) plant fibres [3].

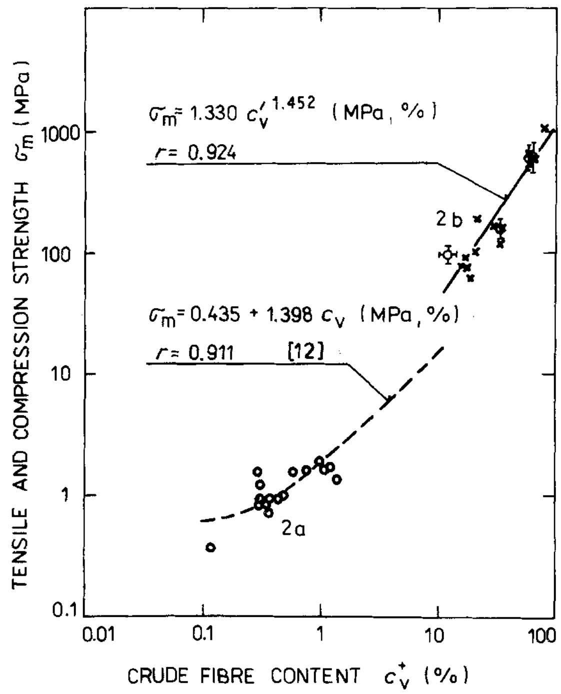

Figure 4 Strength (tensile, compressive) of plant materials plotted against the crude fibre content of the material (defined indentically with Fig. 3). (○) Present study: 2a, vegetables flesh; 2b, dry rye straw stems. (x) Plant fibres [3].

Fig. 3 shows the relation of Young's modulus to c_v^+. Both groups of materials in Fig. 3, i.e. materials characterized by means of c_v and those for which c'_v could be calculated, are approximated by two different relations. The dashed line represents the regression relation for experimental values obtained for vegetable flesh (Fig. 3, 2a) on the basis of simple models [12]. Both relations from Fig. 3 are relatively close approximations of the data for which they were found; however, they differ markedly from each other. It is difficult to say whether the difference is due merely to the different definition of c_v^+ for both data sets or whether it results rather from the anisotropic texture of cellulose in the cell walls of plant fibres [2, 3].

The relation between strength and the crude fibre content for plant materials is obvious from Figs 4 and 5. Although even these figures display indications of inconsistences of the strength–crude fibre content relations for the areas of the higher and lower crude fibre contents, the extent of these inconsistences is much smaller than in the case of the Young's modulus–crude fibre content relation in Fig. 3. Figs 3 to 5 indicate if not the decisive, at least the significant role played by crude fibre in the mechanical properties of plant materials. A more profound understanding of the role of fibres and cell walls in general in the mechanical behaviour of plant materials can be achieved only by a further and more detailed study of the relations between the mechanical quantities and the volume content of cell walls and their components in these materials, accompanied by the parallel elaboration of theoretical models of plant materials with reference to their mechanical properties [12].

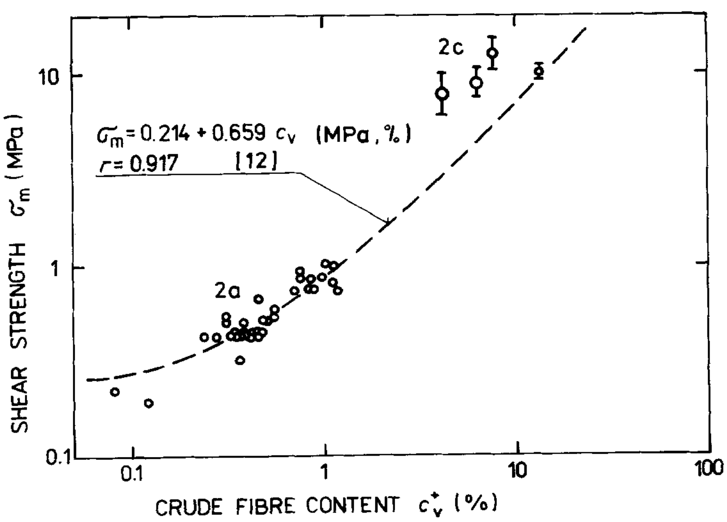

Figure 5 Shear strength of plant materials plotted against the crude fibre content of the material (defined identically with Fig. 3). (○) Present study: 2a, vegetable flesh; 2c, lucerne stalks. (– – –) The regression relation to subset 2a.

4. Conclusions

1. An exponential relation was found between the strength of plant materials and their Young's modulus, relatively well-defined within a wide interval of both quantities and universal for all tested materials. The deviations from this relation were explained by the collapse of the thin-walled air-filled major cells under compressive deformation.

2. Increasing relations between the crude fibre content, on the one hand, and Young's modulus, tensile, compressive and shear strengths, on the other, were determined experimentally. In the case of the relation between Young's modulus and the crude fibre content, an inconsistency in the results was observed in the region of 1 to 10% of the crude fibre content in the sample which, however, could be due to the different procedures of assessing the crude fibre content in the regions below and above the limit of the crude fibre content in the samples mentioned above.

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Received 9 November 1987
and accepted 1 March 1988