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LETTER

As tough as it is delicious? A mechanical and structural analysis of red rhubarb (*Rheum rhabarbarum*)

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So far red rhubarb (*Rheum rhabarbarum*) has been known as a vegetable mostly consumed as desserts and cakes in the early summer, but nothing is known about the potential of its structure as a model for fibre-reinforced sandwich composites. However, natural materials due to thousands or even millions of years of evolution have developed multi-purpose, lightweight and high-efficient structures and provide, therefore, many possible solutions for nowadays optimisation processes and problems.

Red rhubarb, used in China for medical purposes for 4000 years, has been planted in Europe as consumable food since the eighteenth century. Rhubarb is a perennial, dicotyledonous plant that grows from a bulbous rhizome with an epigeous germination. After 1 year, it builds long and thick leaf stalks (petioles) bearing large leaves of up to 1 m^2 in size. The petioles consist of parenchymal soft tissue pervaded by vascular bundles and enclosed by a fibrous bark material [1, 2]. Vascular bundles consist of phloem, xylem and cambium, with the vessels of the xylem cells having a helical texture [3]. The sturdiness of the petioles is based on the intensive activity of the ventral meristem which leads to a secondary thickening [2].

From a technical point of view, rhubarb petioles can be seen as a sort of fibre-reinforced sandwich structure, with the parenchymatic material acting as a foam core matrix and being coated with a stiff and strong layer made of the bark. In addition to the conventional sandwich structure, the rhubarb petioles are pervaded by the thick vascular bundles. Bearing the load of the large leaves, the petioles resemble a beam optimised for bending forces. Mechanical tests were performed to determine the properties of the rhubarb stalks and the single components.

The investigated red rhubarb (*Rheum rhabarbarum*) was grown in Lower Saxony, Germany (Latitude: 52.41°, Longitude: 9.20°) on clay ground interspersed with slate. Plants were harvested on 2 June 2008 and provided as leaf stalks for the test series. The length of the petioles ranged between 600 and 1000 mm. The petioles varied in their thickness ranging between 380 and 740 mm^2 with a characteristic polygonal shape of the cross section which can be seen in Fig. 1.

Six different petioles were analysed by preparing impact and tensile test specimens from the lower, middle and upper section of each petiole. Nevertheless, a direct correlation between mechanical test values and the cross section areas could not be found.

Charpy impact strength investigations were carried out by a Zwick testing machine type 5101 (Ulm, Germany) operating with pendulums of 15 and 50 J. The petioles were cut into specimens with a length of 80 mm and tested according to DIN EN ISO 179 with a pitch of 60 mm. The pendulum axe hits the small side. In total, 18 specimens (3 of each petiole taken from the upper, middle and lower section) were tested in wet (fresh) state.

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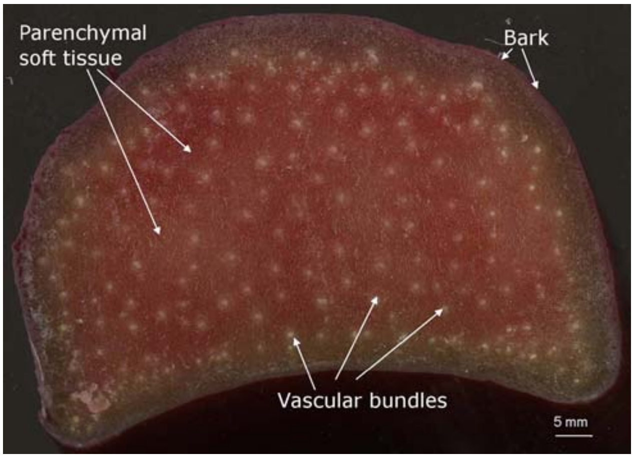

Fig. 1 Photograph of a cross section of rhubarb (the vascular bundles can be seen as *lighted spots* in the parenchymal soft tissue)

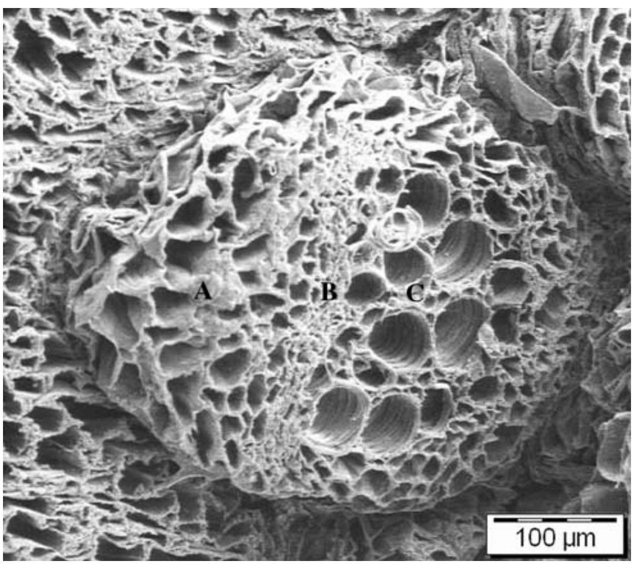

Fig. 2 SEM photograph of a cross section of a vascular bundle consisting of phloem (*A*), cambium (*B*) and xylem (*C*)

Tensile characteristics of the freshly prepared and dried vascular bundles consisting of xylem, phloem and cambium (Fig. 2) as well as the fresh and dried bark bundles were tested in a Zwick/Roell Z020 universal testing machine (Ulm, Germany) according to DIN EN 61 using a Zwick/Roell clip specimen holder with a vulcolan coating on the brackets (Ulm, Germany). The bundles were tested for tensile strength, Young's modulus and elongation at break at a gauge length of 10 mm with a testing speed of 10 mm min^{-1} in both freshly prepared (wet) and dried state. The width of the bark and the vascular bundles was measured from a microscopic photograph of each fibre bundle by the image analysis software ImageJ 1.3.7v by Wayne Rasband, National Institute of Health, USA. Assuming a circular geometry of the vascular bundles, the cross section was calculated with those measurements. The number of vascular bundles per specimen was also counted using the ImageJ software. In total, 360 specimens (15 vascular and 15 bark bundles of each petiole in wet and dry state) were tested. The cross section areas from the fresh vascular bundles of the different petioles ranged between 0.6 and 1.0 mm^2 and the fresh bark bundles ranged between 0.02 and 0.03 mm^2. In the dry state, the cross section was clearly reduced. Cross section areas of the vascular bundles ranged between 0.07 and 0.10 mm^2 and the bark bundles ranged between 0.01 and 0.02 mm^2. The detailed values are given in Table 1.

Morphological examinations were carried out using a Zeiss DSM 940A scanning electron microscope (SEM) (Carl Zeiss GmbH, Jena, Germany). All elements were mounted on aluminium holders using double-sided electrically conducting carbon adhesive tabs and sputtered for 1 min with 56 mA with a layer of gold prior to SEM observations. A high voltage of 10 kV was used for making the micrographs. The SEM images were used to study the fracture surface of the bark and vascular bundles as well as for investigations of the cross section area and longitudinal cuts of the petioles.

Thin cuts from the cross section areas of the petioles were prepared by a razor blade and additionally investigated by an optical microscope Axiostar plus (Carl Zeiss GmbH, Jena, Germany).

Photographs of rhubarb specimens during a Charpy impact test were made by a PHOTRON Fastcam APX-RS high-speed camera (San Diego, USA) with 12,000 frames per second. The assumption for the high elongation at break of the leaf stalks because of the high elasticity of the vascular bundles should be approved by these pictures.

The data of the mechanical investigations ($n = 3$ for each petiole of the impact specimens and $n = 5$ each for vascular and bark bundle specimens of each petiole section in dry and fresh state) were normal distributed according to the David et al. test ($\alpha = 5\%$). Differences between the different sections regarding impact strength or tensile properties of the vascular and bark bundles were not observed (Student's *t*-test, $\alpha = 5\%$). Therefore, the data will be pooled to compare the different petioles directly.

Figure 3 shows the Charpy impact strength. The values of the different petioles reach from 11.3 to 25.6 kJ/m^2 and are, therefore, in the same range as natural fibre-reinforced thermoplasts and thermosets. For example, bast fibre-reinforced polypropylene with a fibre load of 30 mass% reached Charpy impact strength values of 8–25 kJ/m^2 [4], cotton fibre-reinforced poly(lactic acid) with a fibre load of 40 mass% led to an impact strength of 29 kJ/m^2 [5], ramie fibre-reinforced epoxy (fibre load of 40 mass%) led to values of 27 kJ/m^2 [6], wood fibre-reinforced acrylate with a fibre load of 90 mass% led to values of 20–30 kJ/m^2 [7],

Table 1 Tensile properties (mean value of 15 measurements per petiole) of the vascular and bark bundles

Petiole	Fresh state				Dry state			
	Cross section in mm	Tensile strength in MPa	Young's modulus in MPa	Strain in %	Cross section in mm	Tensile strength in MPa	Young's modulus in MPa	Strain in %
Vascular bundles								
1	0.855	1.9	11.3	54.6	0.097	23.2	1076.0	4.1
2	0.824	2.2	14.2	52.1	0.069	24.8	1302.9	3.6
3	1.098	1.1	5.8	44.9	0.149	10.4	621.4	4.0
4	0.835	2.7	14.3	55.0	0.085	26.3	1383.6	2.5
5	0.632	2.3	13.5	50.1	0.092	30.5	1297.7	4.3
6	0.783	2.1	12.8	45.0	0.079	31.1	1347.2	4.0
Mean value	0.838	2.0	12.0	50.3	0.095	24.4	1171.5	3.8
Standard deviation	0.151	0.5	3.2	4.5	0.028	7.5	290.1	0.6
Bark bundles								
1	0.029	61.7	1556.2	13.3	0.013	365.1	18701.7	3.9
2	0.031	55.9	996.7	17.8	0.012	393.0	20101.8	3.3
3	0.029	65.3	1354.8	17.9	0.020	301.7	16393.7	3.5
4	0.027	92.7	2170.3	18.71	0.014	489.7	21745.1	5.0
5	0.020	74.6	1475.4	16.8	0.009	522.7	24599.0	4.5
6	0.029	56.2	1287.1	15.1	0.009	533.8	25063.0	3.9
Mean value	0.028	67.7	1473.4	16.5	0.013	434.3	2100.7	4.0
Standard deviation	0.004	14.0	392.0	1.9	0.004	94.7	3384.1	0.6

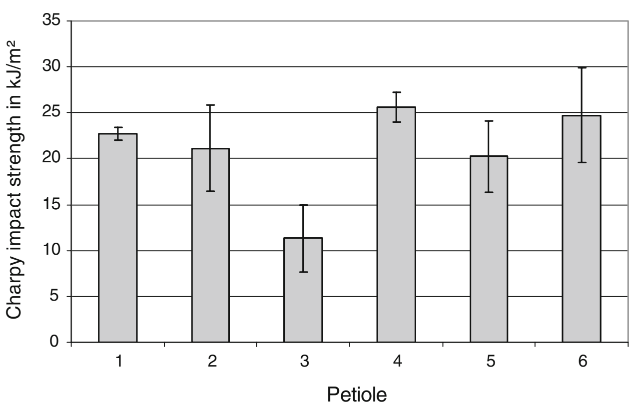

Fig. 3 Mean values of the Charpy impact strength of the different rhubarb petioles. The standard deviation is shown as error bar ($n = 3$ for each petiole)

flax/sisal fibre-reinforced polyurethane with a fibre load of 60 mass% lead to values of 16 kJ/m^2 [8] and ramie fibre-reinforced PTP® with a fibre load of 40 mass% resulted in Charpy impact strength values of 20 kJ/m^2 [6].

The tensile tests of the freshly prepared vascular and bark bundles (Table 1) show that the vascular bundles have a very high strain of 50.3%, but a low tensile strength (2.0 MPa) and Young's modulus (12.0 MPa), whereas the tensile strength and Young's modulus of the bark bundles are, respectively, more than 30 (67.2 MPa) and 120 times higher (1473.4 MPa) but with a strain of about only one-third (16.5%). To compare those values with industrially applied fibres as hemp or flax, dried fibre bundles were also tested in a state conditioned according to DIN EN ISO 139. In this state, the values for tensile strength and Young's modulus of the vascular bundles increased to 10–24.4 MPa (strength) and 1171.5 MPa (Young's modulus). The values of the bark bundles rise to 434.3 MPa (strength) and 21100.7 MPa (Young's modulus). The strain is reduced to 3.8% (vascular bundles) and 4.0% (bark bundles), respectively. The mechanical characteristics of the dried bark fibre bundles are comparable with that of flax (tensile strength: 345–1500 MPa, Young's modulus: 27600 MPa, elongation at break: 2.7–3.2%) [9], hemp (tensile strength: 580–1110 MPa, Young's modulus: 3000–90000 MPa, elongation at break: 1.3–6) [10], jute (tensile strength: 187–773 MPa, Young's modulus: 3000–55000 MPa, elongation at break: 1.4–3.1%) [11] or ramie (tensile strength: 315 MPa, Young's modulus: 23000 MPa, elongation at break: 3.7%) [12].

The differences between bark and vascular bundles might be explained by the different composition of the bundles, which can be shown by the SEM images. Spiral thickenings within the vessels of the xylem cells of the vascular bundles were observed that resemble a helical structure (see Fig. 4). That helical structure of the vessels seems able to absorb a lot of the strain. It is assumed that these spiral thickenings in fresh state can be extended under force load and show high elongations. Spiral

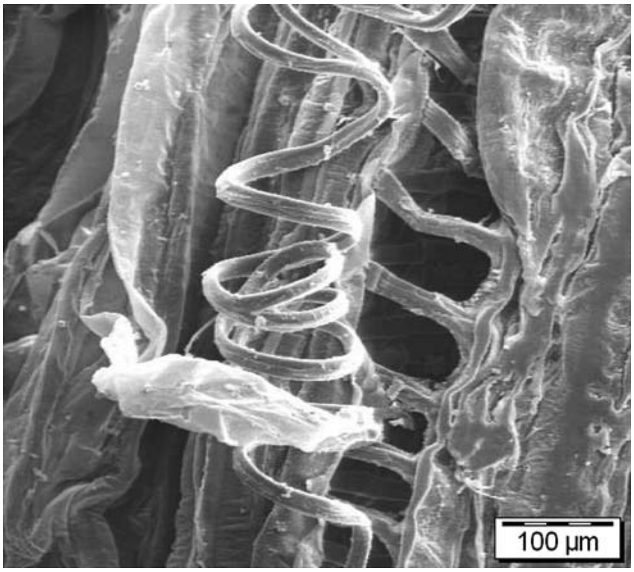

Fig. 4 SEM photograph of spiral thickenings of a vessel (longitudinal cut of a rhubarb petiole)

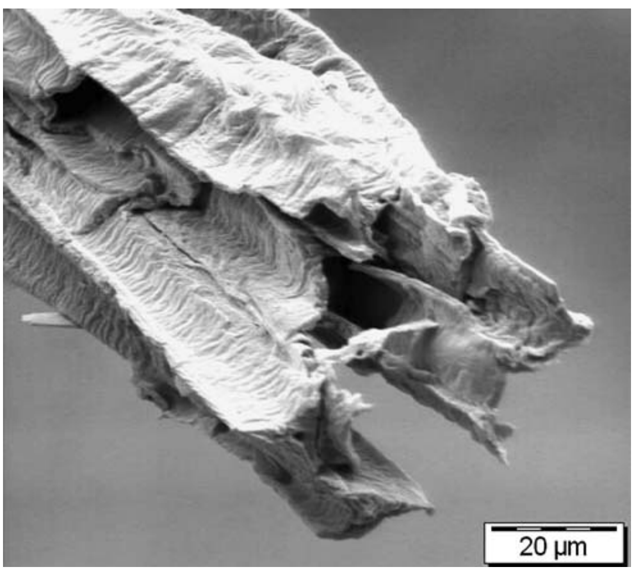

Fig. 5 SEM photograph of a rhubarb bark bundle

thickenings are not present in the bark bundles (Fig. 5), whereas those having a thick cell wall, probably provide the strength and stiffness. The position of the vascular bundles within the petiole can be seen in Fig. 1. In the dry state, the embrittlement of the bundles increases, the spiral thickenings of the vessels cannot be elongated and so the elongation of vascular and bark bundles is approximately the same.

The high-speed shooting of the impact tests shows that the failure mode of the rhubarb petioles probably also contributes to the high impact values. It can be seen that although the crack has travelled through the whole

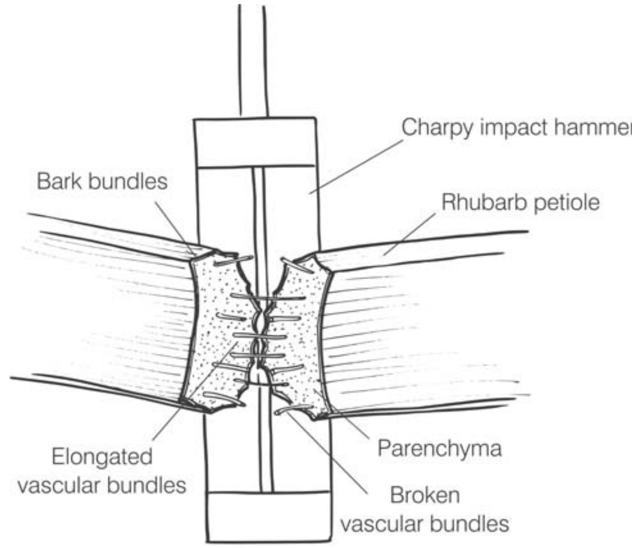

Fig. 6 Fracture mechanism of a rhubarb petiole during impact testing (illustration adapted from the high-speed photograph)

specimen the vascular bundles remain intact, being pulled out of the parenchymal soft tissue and, therefore, probably using up a lot of the break energy (Fig. 6). This is an agreement with the impact failure concept for technical composites (compare e.g. [13–15]).

The mechanical behaviour of the rhubarb petioles is influenced by the form of the petioles as well as the anatomic internal structure. Investigations have shown a higher tensile strength and elongation for the vascular bundles compared to the pure parenchymal tissue. A sample consisting of one vascular bundle and parenchymal tissue resulted in values between the vascular bundle and the soft tissue. It seems plausible that the mechanical properties of the vascular bundles, in particular the high strain caused by the helical structure of the vessels and the debonding and pull-out of the vascular bundle out of the parenchyma, are responsible for the impact behaviour which is supported by an analysis of the correlation between number of vascular bundles per specimen and impact strength. The coefficient of correlation of 0.82 indicates that a linear correlation could be present, although a larger amount of data would be necessary to verify this assumption.

Furthermore, it is very well possible that other factors such as lignification, age and developing stadium (secondary thickening in older petioles), orientation of the vascular bundles in the petioles or the properties of the parenchymal tissue influence the properties of the petiole as a composite.

The analyses of red rhubarb as a fibre-reinforced composite showed some interesting impact properties, especially considering the fact that natural materials are able to compete with industrial materials. Those properties are possibly caused by the interactions of the different components, which will be evaluated in further researches.

As soon as those interactions, the pull-out behaviour of the vascular bundles and their structure are completely understood and can be transferred to industrial applicable materials such as glass and polymeric fibres, and polymers, new lightweight composites, with very high impact strength could be developed.

Therefore, in future, a model and a prototype composite will be generated using the same ratio of tensile properties of the single components as in the rhubarb petioles to analyse whether this is the most important factor and to prove that knowledge about vegetables might be useful not only for chefs but for material scientists as well.

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Engineer Standards

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DIN EN ISO 139:2005: Textilien—Normalklimate für die Probenvorbereitung und Prüfung, in German
DIN EN ISO 179:1996: Kunststoffe—Bestimmung der Charpy-Schlagzähigkeit, in German