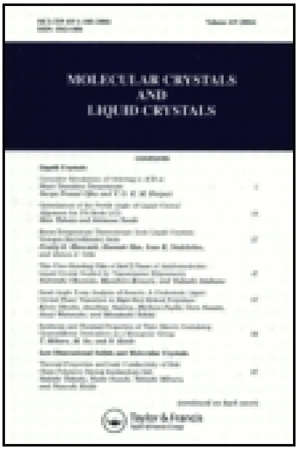

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Mechanical and Thermal Properties of Bast Fibers Compared with Tropical Fibers

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Mechanical and Thermal Properties of Bast Fibers Compared with Tropical Fibers

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The developed and tested hammer mill decorticates bast fibers effectively. The fibers processed are characterized by measured data of the mechanical and thermal properties such as fineness, length distribution, strength, modulus of elongation, impurities, thermo-gravimetric and differential thermal analysis.

The data and parameter of the European bast fibers hemp, flax and linseed do not differ very much from the data of the tropical fibers sisal, jute, kenaf and ramie. Only the fruit fiber coir has essential diverging parameters.

The results can be used for the technical application of natural fibers.

Keywords: fineness; mechanical properties; natural fibers; processing; strength; thermal properties

1. INTRODUCTION

Natural fibers are gaining increasing significance as renewable and environmentally acceptable raw material for technical applications, as well as for civil engineering and building activities. The best known natural fiber plants are flax, hemp, linseed, jute, sisal, kenaf, yucca, abaca and ramie.

However, the bast fibers are a real natural product. Consequently, the mechanical properties are influenced by the variety grown, the growth and weather conditions, the date of harvest, the degree of ripeness at the harvest, the retting procedure as well as by the decortication, processing and cleaning process.

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Particularly the dew-retting procedure of the fiber plants causes a wide variation of the mechanical properties due to biological-bacteriological changes of the material parameters, which are not always kept under constant control.

But the industrial application of the fibers requires large quantities of constant quality. Therefore, processing technologies should be preferred which do not require any retting of the fiber plants, in order to ensure more stabile mechanical properties. Actually, mechanical decortication of the fibers is practiced only, which is based on the hammer mill or breaking roller principle. Other principles such as steam explosion, ultrasonic treatment, enzymatic degumming or chemical processing are in R&D-stage still [1,2]. But each processing principle generates different fiber parameters. Here the quality assurance is one of the main problems of the natural fiber production.

Therefore, investigations have been made to present parameters and data in the following chapters, which represent the properties of natural fibers processed by an advanced hammer mill [3].

2. TECHNIQUE, MATERIALS AND METHODS

The properties and data presented in the following chapters were measured for fibers processed with an advanced technology developed by the Institute of Agricultural Engineering Potsdam [4].

The main process stages are:

Opening of the fiber plant bales by cutting
Shortening of the stalks to an average length of 200 to 250 mm
Monitoring of a continuous mass flow
Decortication by impact stress, circular speed of the hammers approximately 70 m/s
Fiber cleaning by a multiple ultra cleaner in one stage
Opening of fiber bundles by a saw tooth opener

The operational data of the machines were adjusted to the individual type and moisture content of the fiber plants.

Processed and tested were hemp, flax and linseed. The fiber plants were grown and harvested in Germany in 2002 and 2003. The plants were only dried on the fields before harvesting. No retting procedure took place.

The moisture content of the fiber plants after harvesting is in the range of 9 to 12%. The plants were properly stored in a closed shelter to prevent any remoistening.

The fiber fineness is a measure of the degree of loosening up the natural fiber bundles into thinner bundles or elementary fibers. The value of fineness represents the specific mass relative to the fiber length. The usual unit of fineness is "tex". Consequently, the value in tex is equal to the weight of a 1000 m long fiber or fiber bundle. The fiber fineness is measured according to DIN EN ISO 1973.

The substance density of natural fibers amounts to 1.45 g/cm^3 [5]. On the basis of this density, the mean diameter of a fiber bundle can be calculated as an initial orientation for the measured fineness using the following Eq. (1).

$$d = \sqrt{\frac{4 \cdot f \cdot 10^3}{\pi \cdot \rho}} \tag{1}$$

d – Diameter, µm
f – Fineness, tex
ρ – Substance density, 1.45 g/cm^3

The effective length of the technical long fibers after processing are based on the type of plant, the processing technology, the pre-cut length of the stalks and the operation data of the decorticator. The fiber length is measured according to DIN EN ISO 53808. It is a single fiber measurement. The various fiber lengths are separated into 12 classes to calculated the length distribution. Normally, the length distribution is a Gauss Standard curve. However, all fibers shorter than 10 mm are unwanted in many technical application and have to be eliminated from the long fibers during the fiber cleaning. Consequently, the left side of the Gauss curve is cut at 10 mm.

The maximum tensile strength of the fibers were measured according to DIN EN ISO 5079. This strength refers to the fiber fineness. The free clamping length of the sample was 15 mm and the tensile speed 10 mm/min. Simultaneously, the breaking elongation was determined and the modulus of elasticity calculated.

Computer added methods exist in principle to determine the remaining impurities of fibers. However, the fibers have to be decollated very accurately before scanning. Therefore it was preferred to separate all impurities manually and to calculate the percentage by mass. The tested sample size is 100 g each of a previous composite sample mass.

The Thermogravimetry TG of the fibers was investigated according to DIN 51006. The mass of the sample or the change of the mass is measured continuously depending on temperature and/or time.

The temperature of the sample is controlled through the temperature of the stove chamber either by a continuous heat rate $\beta = dT/dt$ or under isothermal conditions (stay-down time). The change of mass is caused by evaporation of volatile components, thermal degradation, reactions or oxidation.

The Differential Thermal Analysis (DTA) was investigated according to DIN 53765. The difference between the temperature of the sample and a reference material of Al_2O_3 is measured depending on the temperature, while the sample and the reference material is heated up by a controlled temperature program. The change of the temperature difference between sample and the reference material indicates exothermal or endothermal reactions of the sample qualitatively or semi-qualitatively.

Furthermore, the differential coefficient of the temperature difference was calculated and is displayed on the right side of the DTA-diagrams. This coefficient represents the speed of the process and the reactions, respectively.

It has to be mentioned that the number of the tests described above was limited because the measurements required are extremely time consuming and expensive. Nevertheless, the data presented can be used as a principle orientation.

All measured parameters of bast fibers are compared with the known data of tropical fibers such as sisal, jute, kenaf and coir to show differences and opportunities for various applications.

3. MECHANICAL PROPERTIES OF THE FIBERS

3.1. Fineness

From a mechanical point of view, the fibers are the natural reinforcement of the stalks of tall fiber plants, which can be compared with steel reinforced concrete.

The fibers themselves are mainly embedded in the peripheral bast ring and are collected into strong bundles. The bundles consist of 10 to 25 elementary fibers. The elementary fibers have a length of 2 to 5 mm and a diameter of 0.01 to 0.05 mm only.

The bundles are connected by lateral ramifications forming a three-dimensional network. The elementary fibers and bundles are cemented by an inter-cellular substance which mainly consists of lignin and pectin. This cementation of the fiber bundles is demolished or dissolved during the decortication in order to extract the fibers. Simultaneously, the strong bundles are cleaved and refined.

TABLE 1 Fineness of Natural Fibers after Mechanical Decortication

Fiber	Fineness tex (equal to g/1000 m of fiber length)	Mean diameter of fiber or fiber bundle (μm)	cV %
1. Fibers processed with the hammer mill			
Hemp	3.9 to 13.7	59 to 110	4.9
Flax	1.2 to 4.1	32 to 60	3.9
Linseed	0.8 to 2.7	26 to 49	6.7
2. Tropical fibers			
Sisal	5.6 to 22.3	70 to 140	–
Abaca	4.1 to 25.6	60 to 150	7.8
Coir	14.0 to 36.0	130 to 190	10.9

The fineness of the fibers after processing depends mainly on the intensity and frequency of the impact stress effected by the working tools of the hammer mill on the fiber surface.

The hammer mill used reaches finenesses shown in Table 1 [6].

If requested, the finenesses of the bast fibers processed can be further improved by modern carding machines.

In any case, the fineness of bast fibers is essentially better than the finenesses of the tropical leaf fibers sisal or abaca with finenesses in the range of 4 to 25 tex. (Table 1).

The thickest natural fiber is the coir fiber with a fineness of 130 to 190 tex only [7].

The pertinent results of the calculated fiber diameters are also shown in Table 1.

3.2. Fiber Length

Fibers for technical applications are decorticated mainly by hammer mills or breaking rollers. The effective length of the technical fibers after processing is based on the type of plant, the processing technology, the pre-cut length of the stalks and the operational data of the decorticator.

After decortication, the length of the natural fibers varies in a wide range of 10 mm to 250 mm. Typical fiber length distributions produced by a hammer mill are shown in Figure 1 [6].

Most of the technical applications, e.g., the needle felt technique or fleece folding machines, require average fiber length of approximately 80 mm, which can be met by adjusting the operation parameters of the hammer mill accordingly.

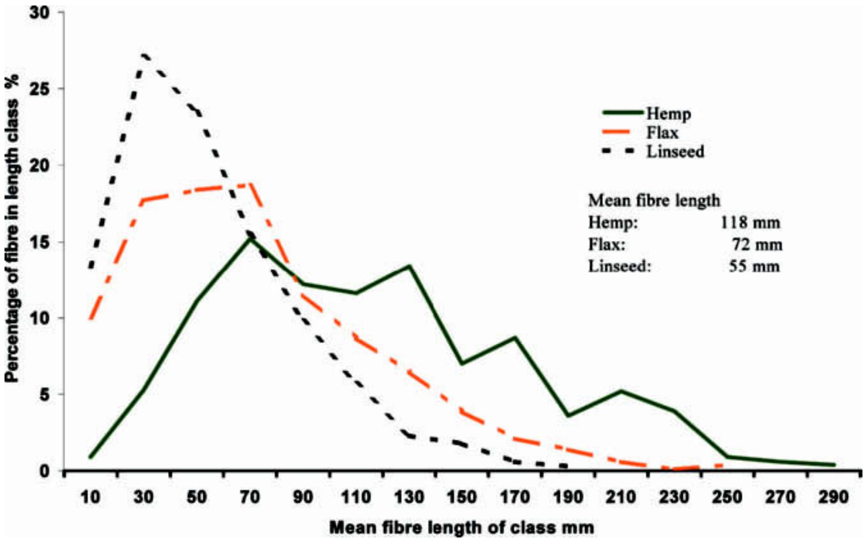

FIGURE 1 Typical fiber length distributions after processing by a hammer mill.

Other techniques, e.g., extrusion of composites, need extreme short fibers. Such fiber length can be best realized by additional defined cutting with special fiber cutting machines.

Such fibers have a comparable length distribution on a lower level (Fig. 2) [6].

These distribution curves show, that the mean fiber length can be adjusted to approximately 4 or 8 mm. The range of tolerance is about ± 5 mm. Only 5% of the fibers are longer than 13 mm. Such a distribution should be suitable for the production of composites in most cases.

3.3. Tensile Strength

Under normal conditions, the following forces and strengths of the fibers produced can be deemed to be measured and ensured (Table 2) [6,8]. Hemp, flax and linseed do not differ very much.

The finer fibers of flax and linseed have approximately the same tensile strength as the hemp fibers. This high performance together with an excellent fineness favors the flax and linseed fibers for application in composites. Ramie, sisal and kenaf have stronger fibers compared with the bast fibers (Table 2).

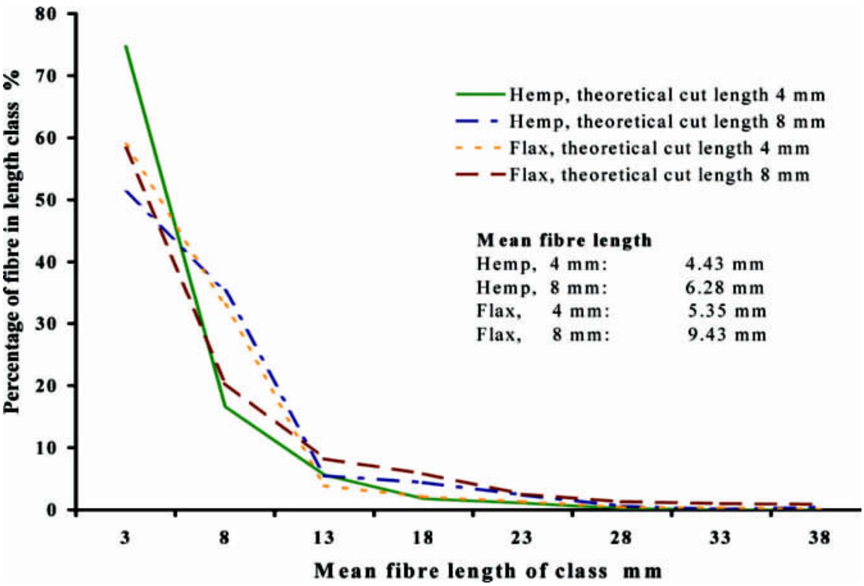

FIGURE 2 Length distribution of the cut fibers.

The tensile force of a single coir fiber is directly comparable with tensile forces of the fiber bundles of bast and the other tropical fibers. However referring to the fineness or the dimensions of cross section, the tensile strength is approximately only a third of the bast fibers or a quarter of the tropical leaf fibers.

TABLE 2 Tensile Forces and Strengths

Fiber	Tensile force[a] (N)	Tensile strength (N/mm^2)	Tensile strength (cN/tex)	cV %
1. Fibers processed with the hammer mill				
Hemp	5.0	490	33.8	23.3
Flax	1.8	640	44.3	21.9
Linseed	1.0	550	38.4	24.3
2. Tropical fibers				
Kenaf	6.4	740	51.1	–
Sisal	6.3	728	50.2	–
Ramie	5.8	673	64.4	–
Jute	4.9	530	36.6	–
Coir	4.0	120 to 240	12.9	12.8

[a]Calculated for a single fiber or a fiber bundle.

The tensile strength of the natural fibers is comparable to the strength of high-tensile steel, which is classified by a strength of $>450\,\mathrm{N/mm^2}$.

3.4. Modulus of Elasticity

The single natural fiber is a three-dimensional body of cells forming a chain. In other words, the natural fiber is a three-dimensional biopolymer. The single fibers are interlinked and twisted into stronger bundles. This structure provides excellent elasticity at a high performance.

The modulus of elasticity of natural fibers depends mainly on the types of plants and the degree of retting. The measured data vary in the range of 24 to $60\,\mathrm{kN/mm^2}$ (Table 3). Tropical natural fibers have approximately the same modulus of elasticity apart from coir, which has an extremely low one.

But in general, the modulus of elasticity of bast fibers is about one seventh of the modulus of steel only. This modulus marks the outstanding tensile stress of the fibers.

3.5. Breaking Elongation

The breaking elongation is a dimension figure of the maximum possible elongation of the fibers. The measured breaking elongations of the bast fibers are in the range of approximately 1 to 2.6% (see Table 3). These elongations of the bast fibers are relatively small in contrast to coir with a breaking elongation of about 17 to 22% [7].

Due to the mentioned facts, the natural fibers have to be chosen carefully for each application in composites and construction components

TABLE 3 Examples of Measured Elongations

Fiber	Modulus of elasticity ($\mathrm{kN/mm^2}$)	Breaking elongation (%)
1. Fibers processed with the hammer mill		
Hemp	30 to 50	1.3
Flax	24 to 40	1.8
2. Tropical fibers		
Kenaf	63	1.3
Sisal	39	2.6
Ramie	41	2.1
Jute	54	1.6
Coir	–	17 to 22

TABLE 4 Remaining Shive Contents of the Fibers after Decortication and Cleaning

Fiber	Average remaining shives content % (mass percentage)
Hemp	1.2
Flax	3.8
Flax*	<0.5
Linseed	4.5
Linseed*	<0.8

*After passing the cleaning stage a second time.

individually requiring high shock resistance or impact resilience, e.g., bumpers of cars.

3.6. Remaining Shive Content

The limit of maximum impurities in the fibers is 2% for most of the industrial applications. Such impurities of the natural fibers are shives and dust.

However, the cleanness of the fibers mainly depends on the efficiency of the decortication and the cleaning stages. The hammer mill used ensures a remaining shive content less than 2% for hemp and less than 4.5% for flax and linseed. Examples are shown in Table 4 [3,4].

The dust is removed by the airflow from the fiber cleaning machines. It can be expected, that the fibers are free of dust.

3.7. Thermal Properties

Hemp, flax and linseed have a similar behavior under temperature. The typical functional course is shown in Figure 3 [9].

Mainly the escort substances of the fibers, such as lignin and pectin cause the deviation of TG and DTA-curves. All tests of TG show that there are 2 phases of mass loss under influence of temperature. The first mass loss of the bast fibers starts at 30°C and ends at a temperature of about 110°C (Fig. 3). The mass lost in this temperature range is approximately 4.5% on an average only and is effected by the evaporation of the adsorbed moisture. Of course, this loss depends on the starting moisture content of the fibers.

The mass of the fiber sample is relatively constant in the temperature range from 110 to 175°C. That means the fibers are thermally

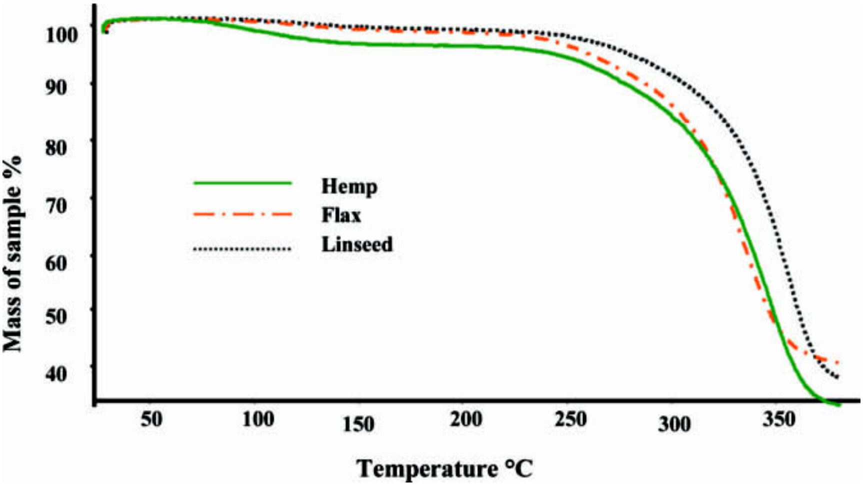

FIGURE 3 Thermo gravimetric analysis of hemp, flax and linseed fibers in atmospheric air.

stabile in this range. The total mass loss up to the temperature of 175℃ is about 6%.

The thermal degradation starts above 175℃. The TG-curve decreases steadily above the temperature of 175℃. The steady decrease is caused

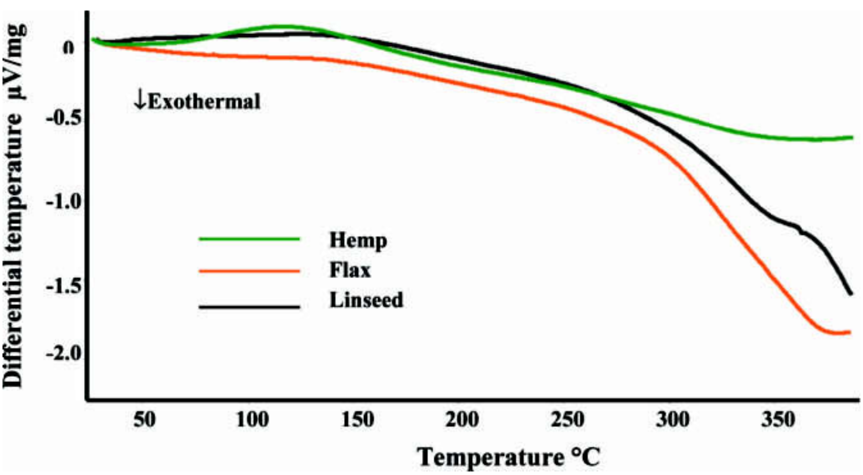

FIGURE 4 Differential temperature analysis of hemp, flax and linseed in atmospheric air.

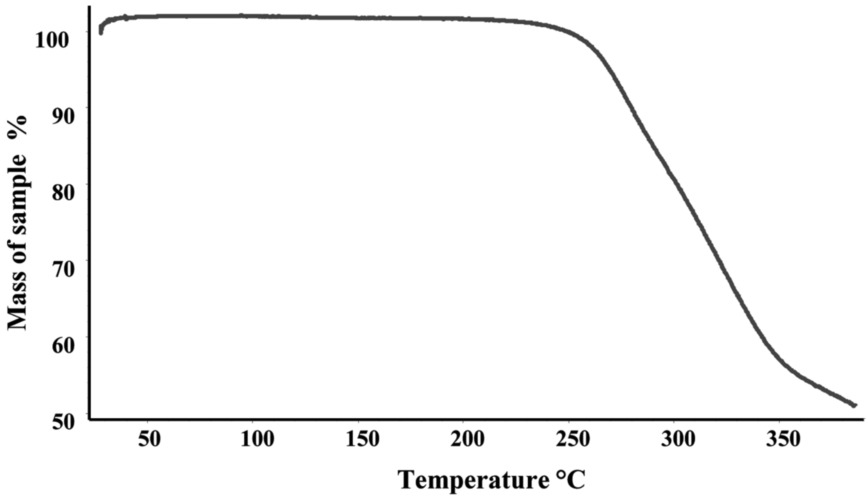

FIGURE 5 Thermogravimetric analysis of coir in atmospheric air.

by an increasing reaction speed. The maximum reaction speed is in the range from 300 to 350°C (Fig. 3). The measured total mass losses at the temperature above 350°C are approx. 60%.

The Differential Temperature Analysis DTA-diagram of hemp, flax and linseed show a different behavior of those fibers (Fig. 4). Hemp

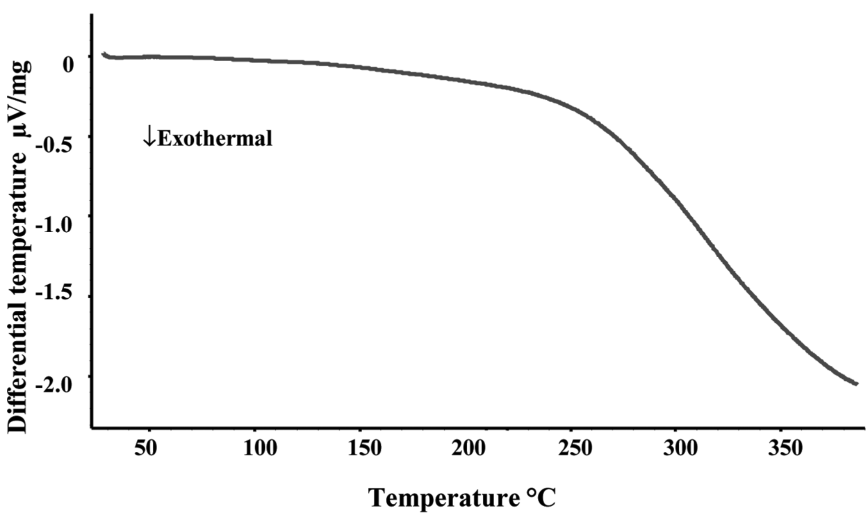

FIGURE 6 Differential temperature analysis of coir in atmospheric air.

and linseed have a lower thermal voltage than flax. The smaller thermal voltage indicates a weaker reaction.

The course of the curves decreases continuously. There are no peaks. The evaporation of the moisture in the range from 20 to 110°C is an endothermal process.

A significant exothermal effect is indicated above the temperature of 110°C up to 400°C caused by oxidation of substances [9].

In contrast to the bast fibers the coir fiber is thermal stabile in the range up to 220°C (Fig. 5). The degradation starts at 225°C and has a steady course up to a total mass loss of approximately 60% at 320°C. The thermal degradation of the coir fibers is an exothermal steady process generating more heat by a higher degradation speed in the shorter range of 250 to 320°C (Fig. 6).

4. CONCLUSIONS

The hammer mill used for decortication of bast fiber plants effect a complete separation of fibers and shives. This facilitates a simple fiber cleaning with remaining impurities of less than 2% for hemp and less than 4.5% for flax and linseed fibers meeting the limits for most technical applications.

The measured finenesses of un-retted hemp fibers vary in the range from 4 to 14 tex and of un-retted flax and linseed in the range from 0.8 to 4.1 tex after the decortication. These finenesses meet the demands of needle felt and fleece folding techniques. For higher-grade finesses the fiber fineness has to be improved using existing carding machines.

The tensile strength of hemp, flax and linseed are in the range from 33 to 44 cN/tex and do not differ essential from the tropical fiber jute. Kenaf, sisal and ramie have a higher tensile strength.

The mean fiber length after decortication by the hammer mill meets the demands of needle felt and fleece folding techniques. If required a further shortening of the fibers should take place after fiber cleaning by defined cutting in an additional process.

The bast fibers desorpt up to 4.5% of moisture in the temperature range from 30 to 110°C. Therefore, the fibers should be dried before the utilization for the manufacturing of composites to prevent any negative effects.

The utilization and processing of bast fibers are unproblematic in the temperature range from 110 to 175°C. The fibers are relatively thermally stabile in this range.

The thermal degradation of the bast fibers starts at approximately 180°C. An essential degradation and damage of the fibers take place at a temperature above 200°C. The bast fibers are not suitable for the processing or utilization at temperatures above 200°C.

The data presented are a first orientation. Further measurements are necessary to ensure these data statistically.

REFERENCES

[1] Allam, A., Konczewicz, W. *et al.* (2004). Degumming of fibrous plants based on osmotic pressure phenomenon. *Journal of Natural Fibers*, *1*, 3.

[2] Leupin, M. (2003). Test results ETHZ Zurich, Personal message.

[3] Munder, F., Fürll, Ch., & Hempel, H. (2004). Advanced decortication technology for unretted bast fibers. *Journal of Natural Fibers*, *1*, 1.

[4] Munder, F., Fürll, Ch., & Hempel, H. (2004). Results of an advanced technology for decortication of hemp, flax and linseed. *Molecular Crystals and Liquid Crystals*, *418*, 165.

[5] Fürll, Ch. (1998). *Test Results of the Institute of Agricultural Engineering*, Potsdam: Germany.

[6] Blacha, J. & Rawluk, M. (2003). Report of fiber testing No. LW/08/03, Research Laboratories of the Institute of Natural Fibers Poznan, Poland.

[7] Lesson, G. (2003). Specifications for coir fiber. *Data collection*.

[8] Anonymous, Measurement of material properties of hemp samples, Test report No. 3.5 P/23/99 and 3.5/73/99, Eastern Thuringia Company of Material Tests for Textiles and Plastics, Rudolstadt-Schwarza, Germany, 2, (1999).

[9] Wilker, V. (2004). Thermo-analytic investigation on bast fibers, Test report, Technical University Cottbus, Germany.