

***Musa textilis* Cellulose Fibres in Biocomposites – An Investigation of Mechanical Properties and Microstructure**

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The mechanical characteristics of cellulose fibres in biocomposites (epoxy resin/*Musa textilis*) were investigated relative to the microstructure of these fibres as determined by porosimetry and electron microscopy in terms of their utilization in composite systems. The influence of the chemical treatment via alkali (NaOH) on the change in surface properties and the interfacial interaction of fibres with an epoxy resin was investigated as well as mechanical characteristics of abaca/epoxy composites. The porosity of abaca fibres reached 57% on average, and the averaged tensile strength value was 641 MPa and a Young modulus of 26 MPa. Evaluated composite systems were prepared through a vacuum infusion in which various orientations of long ordered fibres in these composites were evaluated along with the influence of a 6% NaOH chemical treatment on the resultant mechanical properties. The alkali treatment increased the tensile strength of the observed composite systems by up to 16 MPa. The chemical treatment of the abaca fibres led to an increase in the interfacial interaction, which was evaluated with electron microscopy.

Key words: Porosimetry; Synergic effect; Tensile strength; Vacuum infusion; Water jet

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INTRODUCTION

The utilization of renewable natural resources, *i.e.* cellulose fibres, in an area of composite systems is an environmentally friendly trend. This substitution of synthetic fibres with cellulose-based fibres offers the production of economically acceptable materials that are environmentally friendly and have satisfactory mechanical characteristics. The *Musa textilis* plant, from which cellulose fibres denoted as abaca are gained, grows primarily in the Philippines. These fibres, containing more than 70% of cellulose, are used in an area of textile industry, but they are suitable also for the production of composite systems by virtue of their mechanical characteristics (Jawaid and Abdul Khalil 2011; Yan *et al.* 2016).

Composite materials combine properties of partial components (Madyan *et al.* 2016; Feo *et al.* 2017). They belong among prospective systems that determine the direction of future materials, such as aerogel and other composites and materials, which are created from phases based on natural materials (Das *et al.* 2016; Ruggiero *et al.* 2016b). Currently, many countries emphasize a social-economic expectation in relation to searching for new materials that will have similar mechanical properties as conventionally used systems (Valášek and Müller 2015). New alternatives are needed in the area of

composite material reinforcements when natural fibres have been abundantly used in recent years (Ruggiero *et al.* 2015; Mittal *et al.* 2016; Elsabbagh *et al.* 2017; Valášek *et al.* 2017a). Obtaining fibres from renewable resources saves fossil raw materials and is desirable from an environmental process point of view. The main application area of fibre composites is the automotive industry; according to the European Union regulation, EP Directive 2000/53/EC, the overall recycling rate of vehicles must be 85% and the overall recoverability must be 95%. Automotive manufacturers are currently focusing on their environmental impact from start to finish, from obtaining the raw materials to the manufacturing process, and lastly to disposal. Natural fibres fulfill the assumptions in this industry (Holbery and Houston 2006; Kumar and Das 2017).

The advantages of natural fibres, such as good mechanical properties, low cost, low density, low thermal conductivity, and recyclability, make them a good potential replacement for synthetic fibres in composite materials (Ruggiero *et al.* 2015; Valášek *et al.* 2017b). The natural character of natural fibres is one of their basic disadvantages when it is difficult to determine the exact properties of creating composite systems. This is because fibre properties depend on the place where they grow, actual climatic conditions, and other unchangeable factors (temperature, humidity, rainfall, *etc.*). However, the unambiguous advantages of using natural fillers exceed the disadvantages. Natural fibres are characterized by the fact that they are created by mostly hollow single structures (Müller *et al.* 2016; Otto *et al.* 2017; Valášek *et al.* 2017a). A seemingly circular cross-section of fibres is created from the pores. The porosimetry can be used for the identification of these pores. Mercury intrusion porosimetry is an adsorption technique that uses mercury as the adsorbate. By applying pressure, mercury is forced into the pores of the solid. The mercury volume value (Table 4) that has entered allows one to calculate the area, distribution by pore sizes, and percentage of porosity of the material.

The surface treatment of fibres before their application is an important aspect according to many authors (Xue and Tabil 2007; Le Troedec *et al.* 2008; Punyamurthya *et al.* 2017). Chemical treatments are very widespread surface treatments. They can be treatments in alkali, distilled water, or *via* benzenediazonium chloride.

Abaca fibres are natural vegetable fibres obtained from banana plants that are a leading product grown in the area of the Philippines. Their annual production corresponds to 0.10 million tons (Jawaid and Abdul Khalil 2011; Yan *et al.* 2016). The price ranges from approximately 1.8 €/kg to 2.5 €/kg (Jawaid and Abdul Khalil 2011; Yan *et al.* 2016). Currently, the growth of this plant is expanding into the area of Sumatra and Borneo regions of Southeast Asia. The fibres consist of *ca.* 77% of cellulose, 20% of hemicellulose, and 9% of lignin. They can be up to 9 m in length (Jawaid and Abdul Khalil 2011; Yan *et al.* 2016). A leaching of soluble fractions, *e.g.*, hemicellulose, occurs by means of the alkalis (Le Troedec *et al.* 2008; Iucolano *et al.* 2015).

These fibres have excellent resistance to salt water, and they have good strength (Bledzki *et al.* 2009). Many authors state that abaca fibres create a very weak interfacial interface with matrices, and thus it is suitable to chemically treat the fibres (Le Troedec *et al.* 2008; Van Vuure *et al.* 2015).

Abaca fibres demonstrate enormous potential as reinforcing agents in composite materials. Bledzki *et al.* (2007) state that composites with abaca fibres have worse tensile properties compared with jute composites but abaca fibres increased the impact strength more. Additionally, Haque *et al.* (2010) reported a higher tensile strength of composite materials filled with coconut fibres compared with abaca-fibre systems. A significant

increase in the tensile strength was observed in composite systems with short and long abaca fibres, *e.g.*, 10% of the fibres in matrix. (Vasquez and Diaz 2017).

Abaca can also be used in composite systems in the building industry, in which Iucolano *et al.* (2015) used 2 wt% (abaca fibres in matrix) to the optimization of the toughness, a flexural strength at good workability.

This experiment aims to describe the mechanical properties of fibres from the banana plant *Musa textilis* and to define the composite systems made by the vacuum infusion. Electron microscopy was used for the evaluation of the fibre morphology and to observe the influence of the fibre surface treatment by the NaOH water solution on the change of surface structures. In addition, the mutual interfacial interaction and the influence of the fibre chemical treatment on this interaction were evaluated by electron microscopy. The experimental program focuses on long-fibre composite systems.

EXPERIMENTAL

Materials

Reinforcing phase– Abaca fibres

Abaca fibres were obtained from the plant *M. textilis* that is grown all over the Philippines. For chemical treatment of the fibres, the fibres were treated with a 6% NaOH water solution for 10 h at $24\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$. The concentration of NaOH solution was chosen on a base of cellulose fibre studies (Nam *et al.* 2011; Imran and Adelbert 2015). The alkalis are used for the optimization of the surface morphology. The surface properties are important for the interfacial interactions of all materials (Krolczyk *et al.* 2016; Ruggiero *et al.* 2016a). All fibres were dried at $105\text{ }^{\circ}\text{C}$ before their application into the resin.

Continuous phase- Matrix

The matrix used was created by the epoxy resin suitable for the vacuum infusion, *i.e.*, the resin with extremely low viscosity with good mechanical properties. This resin was hardened with a cycloaliphatic polyamine-based hardener (specifications are shown in Table 1.).

Table 1. Specifications of Used Epoxy Resin and Hardener

Properties	Epoxy resin	Hardener
Epoxy equivalent weight (g/mol)	180 to 196	-
Epoxy index (mol/1000g)	0.51 to 0.56	0.51
Flash Point ($^{\circ}\text{C}$)	150	-
Viscosity (mPa.s at $25\text{ }^{\circ}\text{C}$)	500 to 900	7 to 11
Density (g/cm^3)	1.12 to 1.16	0.93 to 0.96

Preparation of composite systems

Boards with dimensions of $200 \times 300\text{ mm}$ and a height of 4 mm were made by vacuum infusion (30 vol%). A vacuum pump was used for the experiment with a capacity of $55\text{ l}\cdot\text{min}^{-1}$ and an absolute pressure of 100 mbar abs. The fibres were applied on the glass treated with a liquid separator. These fibres were pressed through a press with 5 tons

loading before vacuum infusion was applied. A separating layer and a layer for spreading the epoxy resin were placed on the fibres. Everything was covered with a vacuum foil that was hermetically closed with a vacuum tape. The height of the prepared board with the long fibres was 4 mm. This height was divided into two 2-mm layers. The fibres in these layers were oriented identically (*i.e.*, For 0°/0°, the fibres were oriented in the direction of the loading force during mechanical tests; for 90°/90°, the same preparation was applied but the direction of the fibres during the mechanical tests was perpendicular to the direction of the loading force; for 45°/45°, the orientation of the fibres was 45° shifted to the direction of the loading force; and 0°/90°, where the first layer was perpendicular to the other layer). The test specimens were cut from these boards with a water jet (AW-CT 0806 Awac, Prague, Czech Republic) according to relevant standard ČSN EN ISO 527-1 (2012) (as shown in Fig. 1). Particles of a synthetic garnet (MESH 80, a mass flow of the abrasium was ca. 90 g·min⁻¹) were used for the water jet cutting. Cutting parameters were chosen such as to avoid delamination and a rise of cracks caused by the cut. Thus, the speed of the cut was 100 mm·min⁻¹. The diameter of the nozzle was 0.8 mm. The working pressure was 380 MPa. However, the study did not focus on the evaluation of a suitability of AWJ method for fibre composites with cellulose fibres. The distance of the nozzle from the cutting sample corresponded to 3 mm. A surface roughness on the upper side of the cutted sample corresponded to $R_a = 9.16 \pm 2.16 \mu\text{m}$, $R_z = 49.66 \pm 11.23 \mu\text{m}$ (0°/0°); and to $R_a = 15.00 \pm 0.84 \mu\text{m}$, $R_z = 76.30 \pm 3.83 \mu\text{m}$ (90°/90°) on average at a height of 4 mm. Six test samples from one board were always cut.

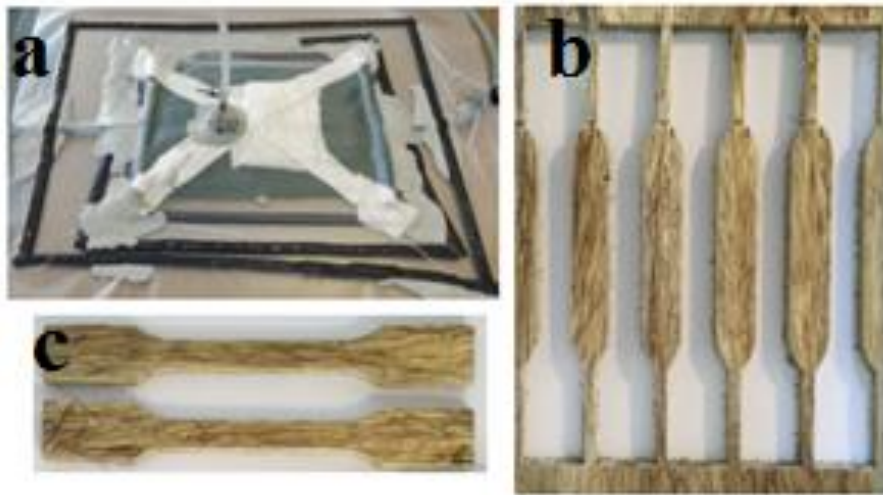


Fig. 1. Preparation process of test specimens: a) vacuum infusion, b) board cut by AWJC technology, and c) all test specimens

The heterogeneity of the test specimens was not disturbed by using the water jet, as is visible in Fig. 2. The water jet cut the specimens according to the standard CSN EN ISO 3167 (2015) by their dimensions, and they were used for the determination of basic strength characteristics of the composite system.

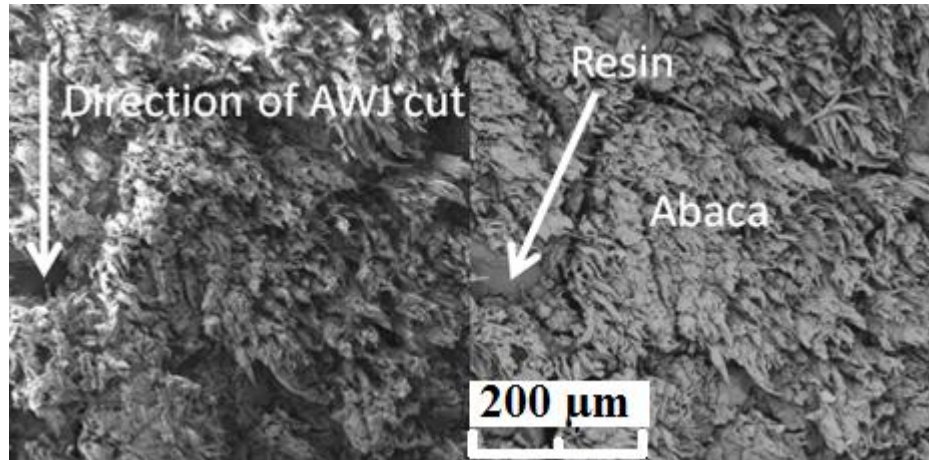


Fig. 2. Surface of composite system exposed to effect of abrasive water jet

Methods

Testing of fibre (abaca) mechanical characteristics – Strength characteristics

A mechanical simulation was conducted using the Hounsfield H10KT machine (Hounsfield Test Equipment, Redhill, UK), and the results were stored and displayed by a software package known as Datahawk by Metrotec (Techlab systems, S.L., Lezo, Spain).

The machine was the vertical test bench type with a test capacity of 10,000 N (Fig. 3). The maximum diameter of the tested samples was 405 mm; with a maximum traverse of the crossbar, excluding the grippers, of 1100 mm. The test machine consisted of a crosshead in which the load cell and grippers were mounted, as shown in Fig. 3. The acceptance limit of the test was that the break of each fibre was to take place at the center of the separation length. This condition occurred for 90% of the samples. The number of test fibres corresponded to 15. Jaws were fitted with rubber inserts which prevent a slippage of fibres. Fibres were always placed perpendicular to the jaws at keeping a constant fibre length.



Fig. 3. Testing of tensile characteristics of abaca fibres

Testing of fibre (Abaca) mechanical characteristics– Porosimetry

The mercury intrusion-extrusion equipment used for the test was a Micromeritics AutoPore IV 9510 (Micromeritics, Norcross, GA, USA) (as shown in Fig. 4). Its resolution in terms of pore size was from 7 nm to 360 μm .

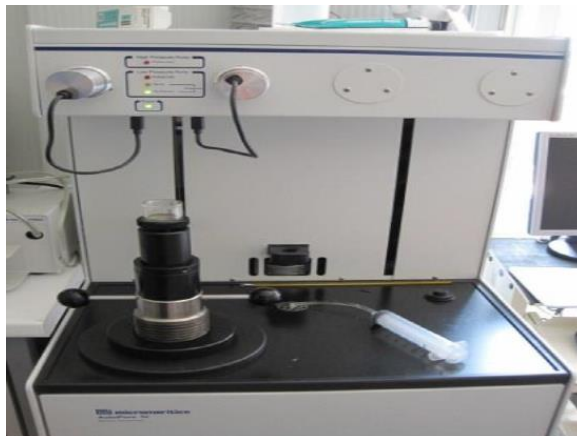


Fig. 4. Mercury intrusion-extrusion equipment

The porosimetry test began with the standardization of the size and shape of the sample, so that its outer surface was uniform and constant. Given the influence of the contact angle on the results, care must be taken to clean the sample by washing it with distilled water if it is considered convenient, as shown in Table 2. The sample was oven-dried at 80 °C for 24 h, and the dry weight of the sample was determined.

Table 2. Hg Parameters

Advancing Contact Angle (°)	141
Receding Contact (°)	141
Hg Surface Tension (γ - dynes/cm)	484
Hg Density (g/mL)	13.55
Abaca Sample Weight (g)	0.273

The second step was the filling and low-pressure porosimetry. Initially the sample was evacuated to remove air and residual moisture or other liquids from the pore system (parameters shown in Table 3). A complete evacuation was important to avoid possible air pockets and contamination issues. The sample cell was filled with mercury as the entire system was still under reduced pressure. Slowly increasing the overall pressure then allows mercury to penetrate the largest pores in the sample or any void spaces between sample pieces. The first data point was taken at a pressure of 3000 Pa to 4000 Pa (0.5 psia). The last data point was taken at a pressure of 7000 Pa (1.02 psia). At the end of this low-pressure part of the analysis, the weight of the penetrometer filled with mercury and the sample was determined, which allows for calculation of the bulk density of the sample (using corresponding blank-runs as a reference). The intruded mercury volume was measured continuously through changes in the capacitance between the column of mercury in the dilatometer stem (capillary tube of known diameter connected to the sample cell) and a coaxial metal sheet surrounding the stem.

Table 3. Porosimetry Parameters for Low-pressure Test

Evacuation Pressure ($\mu\text{m}\cdot\text{Hg}$)	50
Evacuation Time (min)	15
Mercury Filling Pressure (psia)	1.02
Equilibration Rate ($\mu\text{L/g/s}$)	0.1
Maximum Intrusion Volume (mL/g)	0.015

The last step was the high-pressure porosimetry. The sample-cell was transferred to the high-pressure system and it was surrounded by hydraulic fluid, and pressures of up to 414 MPa (60,000 psia) were applied in an isostatic way using the Micromeritics AutoPore IV 9510 (Micromeritics, Norcross, GA 30093-1877, USA), as shown in the attached specifications.

Testing of composite systems

Tensile characteristics were tested by a universal testing machine testing machine LabTest 5.50ST (Labortech s.r.o., Opava, Czech Republic) enabling a maximum load of 5 t. The tests were performed in accordance with the standard CSN EN 527 (2012), and the testing speed corresponded to $6\text{ mm}\cdot\text{min}^{-1}$.

The hardness of the composite systems was experimentally determined in the accordance with the standard CSN EN ISO 2039-1 (2003). A ball of a diameter of 5 mm was used as an indenter, with a loading force of 961 N. The hardness was evaluated in accordance with the standard according to impression depth.

Image analysis

The image analysis of the fibres, fracture surfaces, and interfacial interaction was performed with a Tescan Mira 3 GXM electron microscope (Tescan Brno, s.r.o., Brno, Czech Republic).

The experimentally measured data were evaluated by means of an analysis of variance (ANOVA) and T-test in which a parameter $p > 0.05$ implies a statistically insignificant difference among the means of the compared sets of data using the software program Statistica (StatSoft, Palo Alto, CA, USA).

RESULTS AND DISCUSSION

Physical and Mechanical Properties of Abaca Fibres

Electron microscopy established that the cross-section of the fibres was not entirely a circle but that the fibre contained pores, or so-called lumens. The structure of the abaca fibre and the detailed description of the microstructure are displayed in Fig. 5.

Porosimetry was used for the description of the microstructure. Table 4 shows the results of the mercury porosimetry of the abaca fibre. The volume of the pore was 1.01 mL/mg, which corresponded to a maximum mercury pressure of 59900 (psia), as shown in Fig. 6. The pore diameter value was approximately 3.6 nm for mercury pressure values of 59900 (psia), and 213.9 (μm) for a low-pressure of 1.02 (psia). The average pore diameter of the cylinder-shaped pores was 99.8 nm.

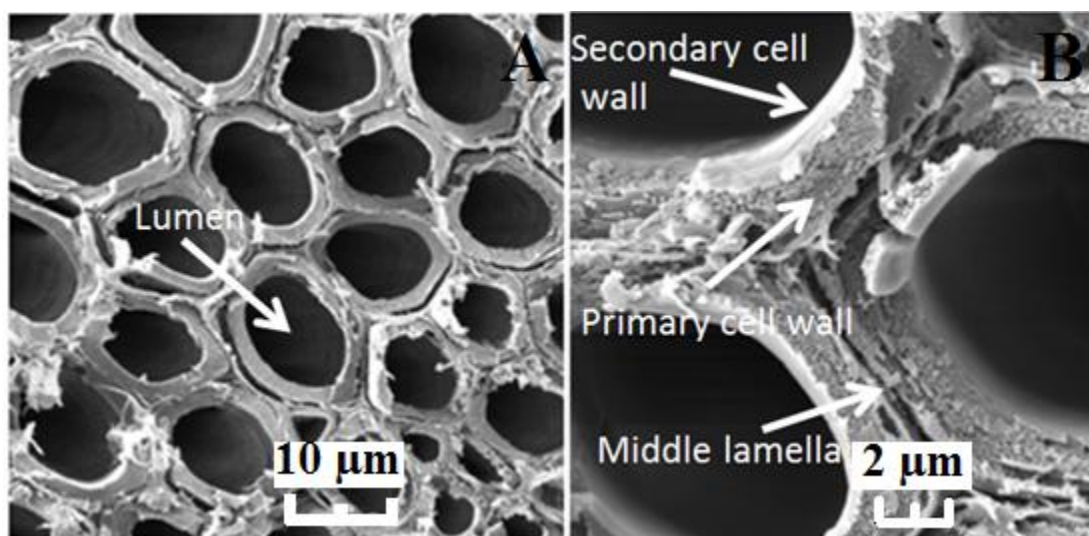


Fig. 5. Microstructure of the abaca fibre: a) under 3.74 kx magnification and b) under 13.7 kx magnification

Table 4. Results of Porosimetry

Total Intrusion Volume	1.01 mL/g
Total Pore Area	40.64 m ² /g
Median Pore Diameter (Volume)	7.715 µm
Median Pore Diameter (Area)	0.016 µm
Average Pore Diameter (4V/A)	0.1 µm
Bulk Density at 1.02 psia	0.57 g/mL
Apparent (Skeletal) Density	1.32 g/mL
Porosity	57.2%
Stem Volume Used	71%

From the analysis of the hysteresis curve (Fig. 6), it was possible to investigate the pore shape of the abaca fibre by comparison of the results present in previous literature. The intrusion and extrusion curve at the highest test pressure have the same pattern of the hysteresis curves of the needles pore shape and spherical pore shape (Liabastre and Orr 1978; Zgrablich *et al.* 1991).

The fibre cross-sectional area is a very important parameter that appears to govern mechanical properties such as tensile strength, Young modulus, and its elongation. For this reason, the geometry of the cross-sectional area was investigated to evaluate the shapes. It was found that the shape of the cross-section of these fibres was approximately circular (Table 5).

The tensile characteristics of the abaca fibres are visible in Table 5. Mekel *et al.* (2016) observed that the average strength of the abaca fibres was 541 MPa and the mean of the abaca fibres was 0.151 mm. The measured results were in accordance with the measurements of Yan *et al.* (2016) and Jawaid and Abdul Khalil (2011), who stated the strength to be between 400 MPa and 900 MPa, an elastic modulus between 6.2 GPa and 20.0 GPa, and the elongation at break as 1.0% to 10.0%. The NaOH treatment of the abaca fibres can also lead to the increase in tensile strength and Young's modulus compared to the untreated fibre (Cai *et al.* 2015). From this point of view, the authors recommend shorter treating times, at *ca.* 2 h and with solutions of approximately 5% NaOH (Cai *et al.* 2015).

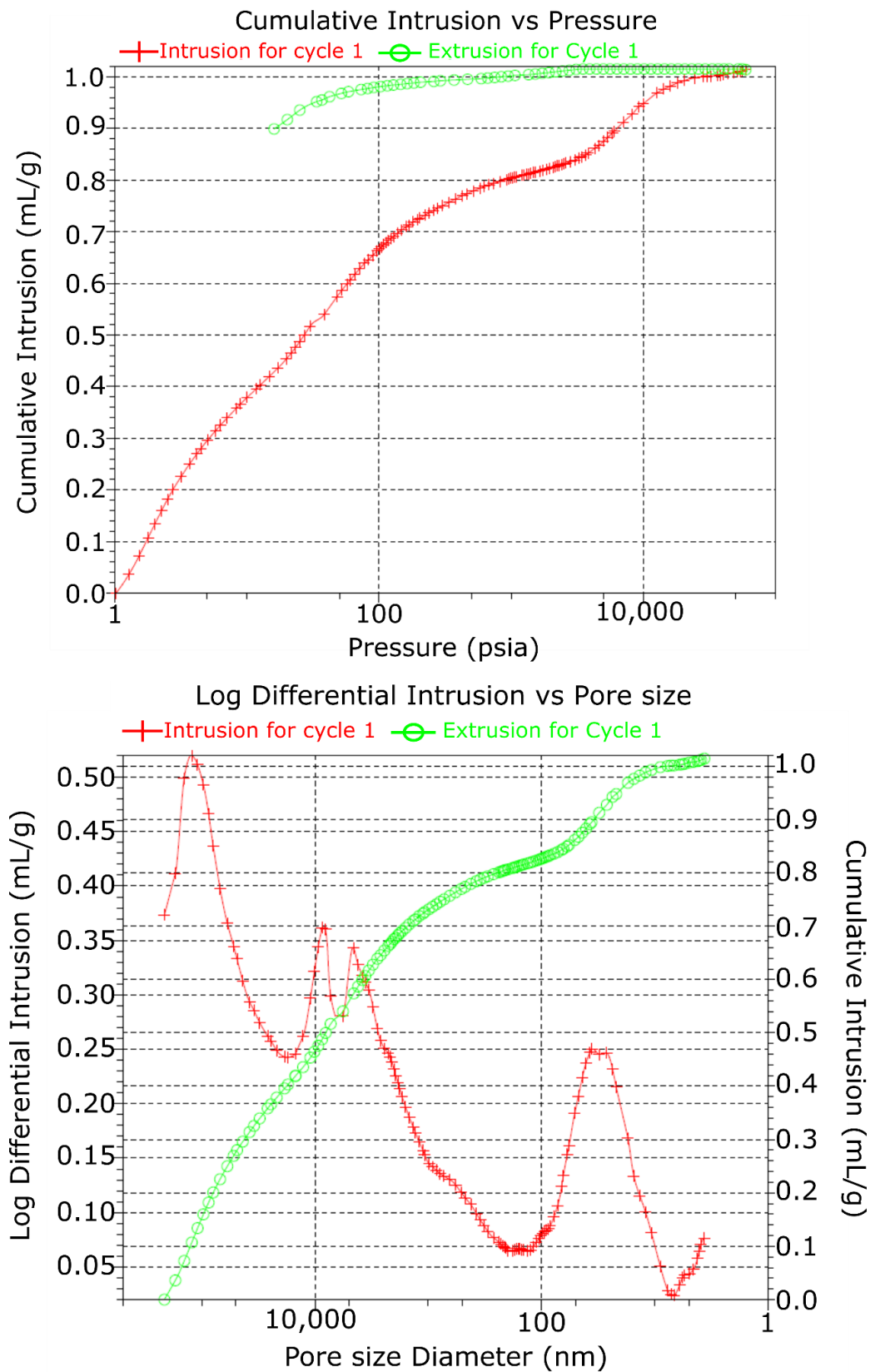
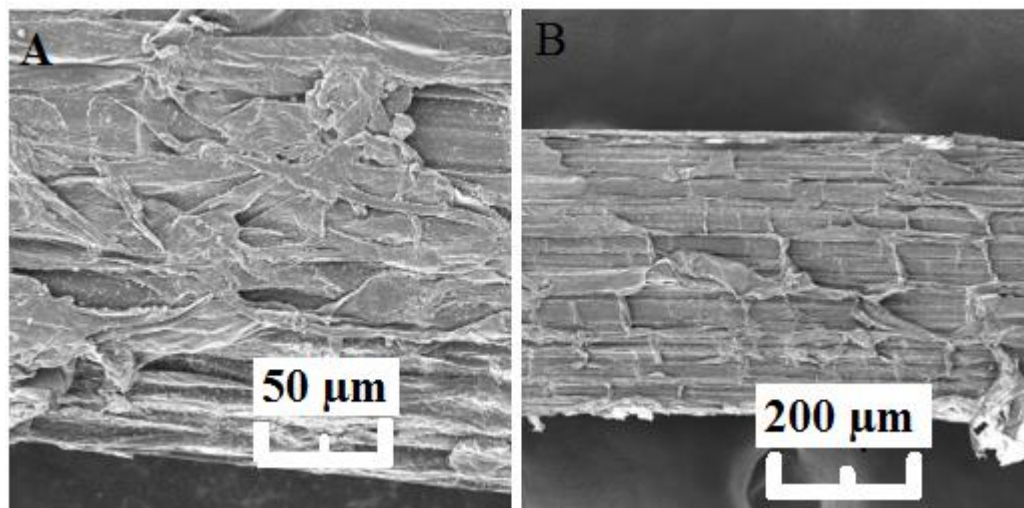


Fig. 6. a) Cumulative intrusion vs. pressure and b) log differential intrusion vs. pore size

Table 5. Mechanical Properties of the Abaca Fibres

Sample	Diameter (mm)	Area (mm ²)	Ultimate Tensile Strength (MPa)	Young Modulus (GPa)	Maximum Force (N)	Breaking Strength (mm)	Elongation at Break (%)
1	0.28	0.062	530.5	30.4	32.7	1.27	2.6
2	0.30	0.071	627.2	28.8	44.3	1.10	2.2
3	0.28	0.062	985.3	24.2	60.7	1.12	2.2
4	0.30	0.071	716.8	24.0	50.7	1.26	2.5
5	0.30	0.071	712.1	21.2	50.3	1.34	2.7
6	0.28	0.062	557.6	23.3	34.3	0.99	2.0
7	0.28	0.062	628.0	21.9	38.7	1.20	2.4
8	0.30	0.071	820.5	19.1	58.0	1.47	3.0
9	0.27	0.057	605.5	29.4	34.7	1.16	2.3
10	0.28	0.062	557.6	30.0	34.3	1.08	2.2
11	0.28	0.062	525.1	27.8	32.3	1.19	2.4
12	0.30	0.071	797.0	27.4	56.3	1.47	2.9
13	0.27	0.057	646.2	32.3	37.0	1.44	2.9
14	0.27	0.057	401.7	19.4	23.0	1.50	3.0
15	0.27	0.057	506.5	24.4	29.0	1.21	2.4
MV	0.28	0.063	641.2	25.6	41.1	1.25	2.1
SD	0.01	0.006	142.0	4.1	11.2	0.15	0.3

Electron microscopy was used for the evaluation of the fibre morphology. Figure 7a, shows the structure of the fibre detail, and Fig. 7b, shows the fibre surface before the chemical treatment with NaOH solution. The alkali treatment of the natural fibres is a common treatment that leads to the increase of the fibre surface due to disruption of hydrogen bonds in a network structure. The chemical treatment of the fibres clearly led to the change of the fibre surface, as shown in Fig. 7.

**Fig. 7.** a) Structure of fibres before treatment and b) surface of fibres after treatment

This was in accordance with the conclusions of many authors who manipulated the amount of surface layers and increased the roughness of the fibres due to the alkali treatment of the natural vegetable fibres. The right treatment of natural fibres increases the roughness of fibres according to Sood *et al.* (2015). The process of the surface treatment

via NaOH solution led to the removal of hemicellulose and lignin. Extended exposure to alkali then leads to dividing single bunches of the fibres, and higher concentrations of 10% to 15% of NaOH lead to a breakdown of the lumen of the abaca fibres due to swelling (Cai *et al.* 2015).

The treatment with NaOH solution led to an increase of a texture of the fibre surface due to removing the cellulose including artificial and natural impurities from the fibre surface. Also a layout of units in the cellulose macromolecule is influenced due to the alkali environment, which influences the resultant mechanical properties of the fibre (Valadez-Gonzales *et al.* 1999).

Mechanical Properties of Abaca/Epoxy Composites

The inclusion of the abaca fibres led to a decrease of the system hardness. The value of the unfilled resin corresponded to 132 ± 21 HB (hardness by 961 N), and the values of the composite system are presented in Fig. 8. Based on the measurements, it was shown that the fibre orientation at the same concentration of the filler in the matrix did not influence the resultant hardness. Neither the fibre orientation nor the chemical treatment demonstrably influenced the resultant hardness of the composite systems ($p > 0.05$).

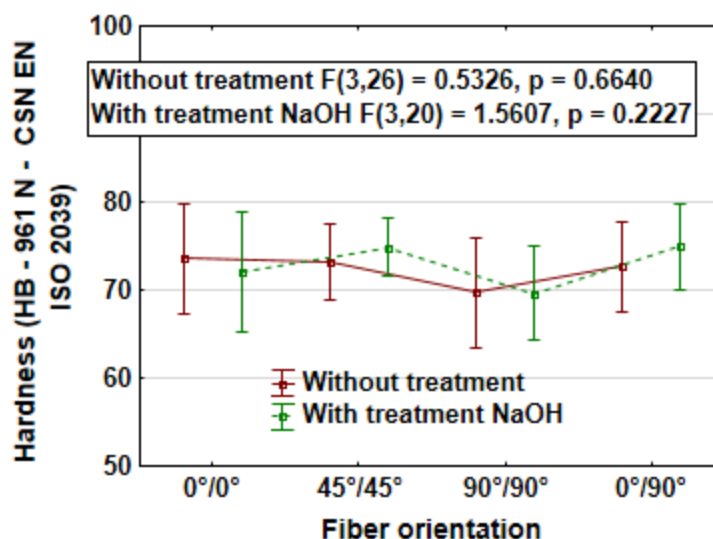


Fig. 8. Hardness of composites with abaca fibres with different orientations

The strength values of the composite systems with different orientations of fibres and different surface treatments are presented in Fig. 9 (0°/0° represents a 4-mm layer in the direction of tensile stress, 90°/90° represents a 4-mm layer perpendicular to the direction of tensile stress, and 0°/90° represents fibres in two layers, both 2 mm with different orientations). The unfilled resin reached the tensile strength values of $44.5 \text{ MPa} \pm 3.3 \text{ MPa}$. In terms of the tensile strength, the optimum arrangement of the fibres was in the lengthwise direction to the direction of the loading force. In this case, the increase in strength occurred compared to the unfilled resin of 80.7 MPa (and the variation coefficient did not exceed 11%). For the composite orientated in two perpendicular layers (0°/90°), an increase in strength of up to 47.0 MPa occurred. At the orientation of the fibres perpendicular to the direction of the loading a decrease in strength of up to 41.3 MPa on average (90°/90°) and 26.5 MPa on average (45°/45°) occurred compared with the unfilled resin. A significant dispersion of the values occurred—the variation coefficient 28%.

Vasquez and Diaz *et al.* (2017) demonstrated the increase in the strength of the composites with the alkali-treated abaca fibres of 6.9 MPa, namely by means of increasing the interfacial interaction, which was obvious under scanning electron microscopy (SEM) analysis.

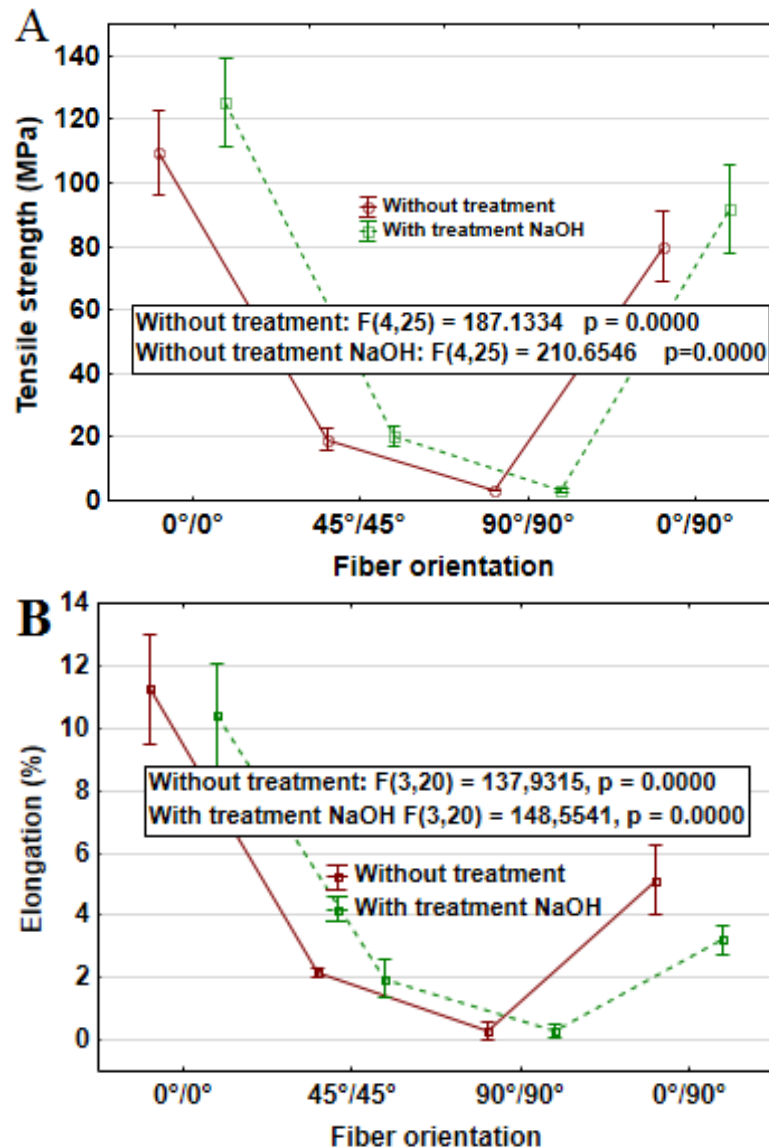


Fig. 9. Tensile characteristics of composites with abaca fibres with different orientations: a) tensile strength and b) elongation

The average tensile strength value for the composites with NaOH-treated fibres was 15.6 MPa (0°/0°) and 11.5 MPa (0°/90°), higher than the strength of systems without treatment. This increase can be attributed to increasing strength characteristics of NaOH-treated fibres in accordance with conclusions of a study of Cai *et al.* (2015). When statistically comparing the tensile strength of composite systems with the untreated and treated fibres, the influence of this treatment on the resultant strength was not proved ($p > 0.05$) in the significance level of 0.95, as shown in Table 6. A typical failure of the test specimens after the static tensile test is presented in Fig. 10. The failure occurred with a

partial pulling out of the fibres in the direction of the affecting force. Provided that the direction of the loading force cannot be estimated in advance, the use of the composite system with different orientation of the layers ($0^\circ/90^\circ$) seems to be suitable.

Table 6. Statistical Comparison of Tensile Strength Between Composites with Fibres Treated by NaOH and Composites with Untreated Fibres (T-test)

$H_0: \mu_1 = \mu_2$ ($p > 0.05$)	T-test			
	$0^\circ/0^\circ$	$45^\circ/45^\circ$	$90^\circ/90^\circ$	$0^\circ/90^\circ$
	0.06	0.83	0.76	0.12



Fig. 10. Different types of failures of specimens

The increase of the fibre roughness leads to an improved interaction with polymeric materials (Dalmay *et al.* 2010). This increased interaction was possible to observe by SEM analysis on the interfacial interaction of test specimens, as shown in Fig. 11. However, the increase of the interfacial interaction did not significantly reduce the propensity of the composites to a failure by a transversal mechanism.

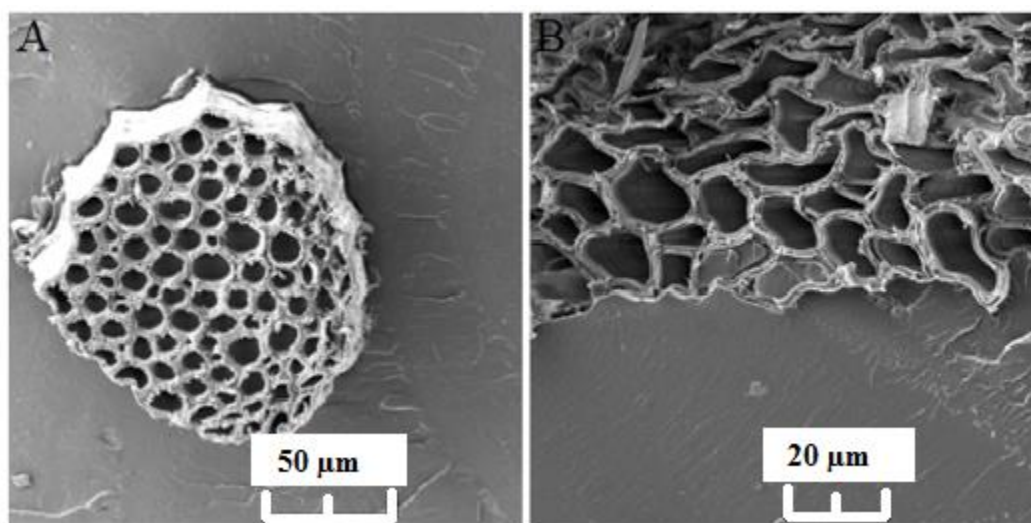


Fig. 11. a) Interfacial interaction before fibre surface treating and b) detail of interfacial interaction after fibre treatment by NaOH

This finding was evident in the results of the tensile strength of the composites ($45^\circ/45^\circ$) and ($90^\circ/90^\circ$), when it did not come to the significant increase of the strength characteristics in the comparison of treated and untreated fibres (Fig. 9). The failure of

these composites was similar as in a study of Zuccarello *et al.* (2017a). A single-fibre pull-out test can be used for a definition of the interfacial interaction itself which *e.g.* Zuccarello *et al.* (2017b) use for biocomposites.

CONCLUSIONS

This study evaluated the possibilities of abaca fibre utilization in composite systems. The tensile strength of observed long-fibre composite systems increased due to the chemical treatment of the fibres. The fibres described in this experimental program are another alternative to commonly used fibres such as coir or sisal. The most important conclusions are as follows:

1. Analysis by scanning electron microscopy (SEM) demonstrated the influence of the alkali treatment by the NaOH solution on the surface structure of the fibres through removal of the surface layers and the increase in roughness.
2. The SEM analysis showed the optimization of the interaction of the abaca fibres and the epoxy resin due to the alkali treatment.
3. The composite systems with treated fibres showed higher tensile strength values on average, but because of the variation coefficients of the measurements, this increase was evaluated as statistically non-demonstrable, with the significance level of 0.95
4. The increase of the tensile strength of composites (0°/0°) with treated fibres of 15.6 MPa was caused by the optimization of mechanical properties of the fibre due to the alkali treatment.
5. The interfacial interaction between NaOH treated fibres and the epoxy resin was not so significant in order to lead to the increase of the strength characteristics of composites (45°/45°) and (90°/90°) – *i.e.* the reduction of the composite propensity to the failure by transversal mechanisms – dividing matrices from fibres.
6. Mechanical properties of composites (0°/90°) are given by the combination of the effect caused by increasing the strength characteristics of treated fibres and the failure by transversal mechanisms.
7. The hardness of the composite systems was decreased by the fibre inclusion.

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