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ORIGINAL RESEARCH

Influence of the alkali treatment on the sorption and dielectric properties of woven jute fabric

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Abstract Woven jute fabric was treated with sodium hydroxide solution of different concentrations at room temperature, for different periods of time. After that, jute fabrics with gradually decreased content of hemicelluloses were obtained. The changes of the sorption properties (moisture sorption, water retention power and degree of fiber swelling) and dielectric properties (effective relative dielectric permeability, AC specific electrical conductivity and dielectric loss tangent) of alkali treated jute fabrics were investigated. After the alkali treatments, the degree of accessibility of the cell wall components to water vapor increased with increased severity of the alkali treatment. In parallel, the degree of fiber swelling and total water holding capacity of the fabrics were increased. The dielectric properties are very sensitive to fabric structural characteristics, chemical composition and its ability for moisture sorption. Thus, the obtained increase of the effective relative dielectric permeability after the alkali treatments can be attributed to the changes in the structural characteristics and decrease in the content of hemicelluloses, which further contributed to an increased ability for moisture sorption. The changes in the AC specific electrical conductivity can be explained by the fact that the hemicelluloses not only restrict the freedom of the water molecules to take part in the polarization process, they also change the structure in such a way that the mobility of the ions in the electric field is restricted. The values of dielectric loss tangent increased after the alkali treatments due to the increase in the number of polar groups.

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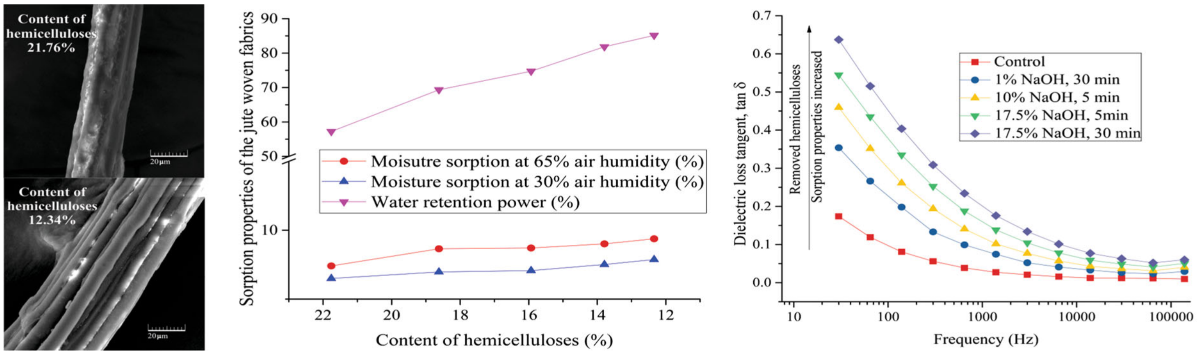
Graphical abstract



Keywords Jute · Alkali · Hemicelluloses · Sorption properties · Dielectric properties

Introduction

In recent years, bast fibers have become a focus of intense interest. From the point of usage, global consumption, production and availability, the only bast fiber that can be called a major fiber is jute. Commercially grown in India, Bangladesh, China and Nepal, the jute (*Corchorus capsularis* L. and *Corchorus olitorius* L.) is the second most important abundant fiber after cotton. Being a coarse, hard and mechanically stable fiber, jute has been traditionally preferred as packaging material i.e. sacking cloth, hessian, etc. (Rahman 2010). About 15% of the world's jute fiber consumption is used to make jute fabrics for carpet backing (Krishnan et al. 2005). Currently, the jute fibers are increasingly used as important raw material for industrial application and production of different composites because of their extraordinary properties, such as high tensile strength and tenacity, high modulus of elasticity, high absorbency and hygroscopicity, good thermal and electrical properties, biodegradability, low density, renewability, recyclability, low carbon footprint, etc. (Krishnan et al. 2005; Rahman 2010).

As a lignocellulosic fiber, jute has a very heterogeneous chemical composition, which includes three main components: α-cellulose (58–63%), hemicelluloses (21–24%) and lignin (11.4–12.0%), as well as minor components such as water solubles, fats, waxes and pectin (Krishnan et al. 2005). The location of the main chemical components within the fibers is well known (Krishnan et al. 2005). Namely, the α-cellulose forms the bulk of the ultimate cell walls with the molecular chains lying broadly parallel to the fiber axis (Krishnan et al. 2005). It is rich in hydroxyl groups, which partially affects the moisture sorption of the jute fibers. The highly crystalline cellulose fibrils, which provide stiffness of the fibers, are embedded in a matrix composed of hemicelluloses and lignin (Baltazar-y-Jimenez and Bismarck 2007). Hemicelluloses, which generally differ from the cellulose with respect to their solubility in alkalis and the lower degree of polymerization, are strongly bonded by hydrogen bonds with the cellulosic fibrils. They are amorphous cell wall components which occupy the space between the fibrils in both the primary and secondary wall (Gümüşkaya et al. 2007). Lignin is a long-chain substance, located in the middle lamella and secondary wall, providing rigidity and thermal resistance of the cell wall (Krishnan et al. 2005). The lignin has very low reactivity due to the presence of strong carbon–carbon linkages and other aromatic chemical groups, which contributed to its limited degradation or fragmentation (Kostic et al. 2008; Pejic et al. 2008).

The location of the non-cellulosic components within the fibers, as well as the fiber chemical composition, which depend on the growing conditions and geographical location for cultivation, are the most important factors that influence the jute fiber properties. A high content of non-cellulosic components in the jute fibers has a negative influence on their properties and processing, which contributed to their limited application. Therefore, it may be necessary to further process the jute fibers to reduce the content of some non-cellulosic components and to improve some fiber properties (mechanical, sorption, dielectric, etc.). The chemical treatments have been widely used to remove non-cellulosic components, among them, the alkali treatments have been used for years as the most direct, economical and efficient chemical treatments to remove the hemicelluloses from the bast fibers. Also, alkali treatments are an important tool for investigating the relationship between structure and fiber properties. The effect of the hemicelluloses removal on the structure and properties of lignocellulosic fibers such as hemp (Kostic et al. 2008, 2010; Pejic et al. 2008, 2009) and flax (Lazic et al. 2018) have been studied in detail. According to our knowledge, there is limited available literature dealing with the influence of the chemical composition on the jute fiber properties. Mukherjee et al. (1993) and Ray and Sarkar (2001) investigated the influence of the chemical composition on the mechanical properties of jute fibers. Considering the above mentioned, in this study, woven jute fabrics alkali treated with sodium hydroxide solution under different conditions were used to investigate the influence of the structural characteristics and content of hemicelluloses on the sorption and dielectric properties of jute fabrics. These two properties should be analyzed in parallel having in mind the complexity of measuring the dielectric properties of fibrous materials, especially fabrics containing moisture, as it has been demonstrated by Bal and Kothari (2014). The same authors (Bal and Kothari 2009, 2010) referred to the fabric as the “fiber–moisture–air” system, and as such is very sensitive to changes in fibrous material structure and moisture sorption properties. In the case of the alkali treated jute fabrics, any shrinkage of the treated fabrics would cause changes in their structure and consequently their sorption and dielectric properties. Therefore, an attempt has been made to determine and analyze the dielectric properties of hygroscopic alkali treated woven jute fabrics considering their structural characteristics, chemical composition and sorption properties.

The sorption properties (moisture sorption, water retention power, the degree of fiber swelling) and dielectric properties of alkali treated woven jute fabrics, were investigated as very important properties which influence their processing and end-use. Furthermore, the dielectric properties of fabrics are indirect indicators of the tendency of the fibrous materials to generate static charge (Asanovic et al. 2018; Cerović et al. 2014), which makes the determination of these properties very important. The textile materials with higher dielectric properties, such as effective relative dielectric permeability, AC specific electrical conductivity and dielectric loss tangent are particularly stable to achieve good energy accumulation in the presence of an electric field (Markiewicz et al. 2009) and they can be successfully used in flexible electronics, as well as, for electrical application such as electrostatic discharge and fabric-based electromagnetic shielding devices (Nurmi et al. 2007) etc. Except for the above mentioned high performance technologies, woven jute fabrics with higher dielectric properties can be also used for some ordinary products, such as protective clothes or textile of specific behavior in environments sensitive to electrical discharges, home textiles (carpet), filters (static charge causes impairment of filtering properties as well as the fire risk that can be caused by the spark appearance).

Experimental

Materials

Commercially produced raw woven jute fabric in plain weave with the following chemical composition: 1.88% water solubles, 1.92% fats and waxes, 0.84% pectin, 13.48% lignin, 21.76% hemicelluloses and 60.09% α-cellulose, (chemical composition determined according to the procedure described in methods, Garner 1967) was used in this investigation as experimental material. All used chemical agents obtained from commercial sources (Suppl., Materials) were of analytical grade and used without further purification.

Methods

Alkali treatments

The raw woven jute fabric was treated with 1% and 17.5% NaOH solution for 30 min and with 10% and 17.5% NaOH solution for 5 min, 1:50 liquid ratio. The alkali treatments were done at room temperature. They were followed by neutralization with 1% acetic acid, then, woven jute fabrics were rinsed with 0.5% $NaHCO_3$, washed and dried at room temperature for 72 h. Altogether, four alkali treated woven jute samples (H30/1, H5/10, H5/17.5, and H30/17.5) and untreated sample (C) were investigated, Table 1.

Determination of weight loss and chemical composition of woven jute fabrics

The weight loss (WL), which occurs after the alkali treatment of woven jute fabrics, was determined by direct gravimetric method (Koblyakov 1989) according to the Eq. (1):

$$WL(\%) = \frac{m - m_a}{m} \cdot 100 \tag{1}$$

where: m (g) is the mass of absolutely dry untreated woven jute fabric and m_a (g) is the mass of absolutely dry alkali treated woven jute fabric.

The chemical composition of woven jute fabrics was determined according to the modified procedure described by Soutar and Bryden (Garner 1967). In brief, the non-cellulosic components were successively removed in the following order: water solubles (extraction with boiling water for 30 min), fats and waxes (Soxhlet extraction with dichloromethane for about 4 h), pectin (extraction with 1% ammonium oxalate at boiling temperature for 1 h), lignin (extraction with 0.7% $NaClO_2$ at boiling temperature for 2 h) and hemicelluloses (treatment with 17.5% NaOH at room temperature for 45 min). After removal of the non-cellulosic components, α-cellulose remains as a solid residue.

Characterization of woven jute fabrics

The jute fiber surface chemistry was characterized using Attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR). The transmission spectra were obtained using Shimadzu IRA Infinity-1 (FT-IR) spectrophotometer equipped with attenuated total reflectance accessory (ATR) using a diamond/ZnSe crystal in the wavenumber range of 4000–600 cm^{-1}, at a resolution of 2 cm^{-1} and in 20 scan mode. Before measurement, woven jute fabrics were dried overnight at 40 °C and stored in a desiccator.

The fiber surface morphology was studied by field emission scanning electron microscopy (FESEM, Tescan MIRA 3 XMU) at 20 kV. The samples were sputter-coated with Au/Pd alloy before analysis.

Structural characteristics and air permeability of woven jute fabrics

The structural characteristics of woven jute fabrics were characterized by the yarn density in fabric, fabric thickness, fabric weight and fabric porosity. The yarn density in fabric (a number of yarns per unit length) was determined according to the standard EN 1049-2:1993 (1993). The fabric thickness, as well as the yarn diameter, was measured on a thickness tester (AMES 414-10) under pressure of 10 kPa. The fabric weight was determined using the standard ISO 3801 (1977). The porosity (P) was calculated according to the following Eq. (2) (Asanovic et al. 2015):

$$P = 100 - 100(d_0 g_0 + d_p g_p - d_0 g_0 d_p g_p) \tag{2}$$

where d_o (cm) and d_p (cm) are the diameters of the warp and weft yarns; g_o (cm^{-1}) and g_p (cm^{-1}) are the warp and weft yarn densities of the investigated woven fabrics.

The air permeability was tested on the Air Permeability Tester (M021A) at a constant pressure of 100 kPa (20 cm^2 test area) according to the standard EN ISO 9237:1995 (1995).

Table 1 Weight loss and chemical composition of untreated and alkali treated woven jute fabrics

Sample code	Explanation	Weight loss (%)	Hemicelluloses (%)	Lignin (%)	α-cellulose (%)
C	Control, untreated	/	21.76	13.48	60.09
H30/1	1% NaOH, 30 min	5.87	18.62	13.45	67.93
H5/10	10% NaOH, 5 min	8.63	15.93	13.63	70.44
H5/17.5	17.5% NaOH, 5 min	10.35	13.79	12.91	73.31
H30/17.5	17.5% NaOH, 30 min	12.07	12.34	13.27	74.35

Determination of sorption properties of woven jute fabrics

The sorption properties of woven jute fabrics were characterized considering the changes in moisture sorption, water retention power and degree of fiber swelling.

The moisture sorption (MS) was determined by the thermogravimetric method (Kothari and Bal 2010) using an infrared moisture analyzer (Sartorius MA 35). Prior to moisture sorption measurement, jute fabrics were exposed to different relative air humidity (30% and 65%) for 24 h. The average of three measurements for each sample was considered.

The water retention power (WRP) was determined according to the standard centrifuge method ASTM D 2402-78 (1978) and calculated using the Eq. (3):

$$WRP(\%) = \frac{m_c \cdot 100}{m} - 100 \tag{3}$$

where m_c (g) is the mass of jute fabric after immersing in distilled water at room temperature for 1 h and centrifuging at 5000 rpm for 5 min and m (g) is the mass of absolutely dry jute fabric. Reported values of water retention power are the average values of six parallel measurements.

The degree of jute fiber swelling was determined as the cross-sectional swelling of the fibers in distilled water by following changes in the fiber diameter. The fibers from both the untreated and alkali treated jute fabrics, in dry conditions, were placed between two thin glass plates with a drop of distilled water. The fiber swelling, for a different period of time (5, 10, 15, 30, 60 and 120 min), was recorded by a light microscope Ergaval (Carl Zeiss-Jena), equipped with a live capture camera system. The fiber diameters before (d_0, μm) and after (d_s, μm) swelling were determined using Axio Vision 4 software. The degree of fiber swelling (DS) was calculated using Eq. (4):

$$DS(\%) = \frac{d_s - d_o}{d_o} \cdot 100 \tag{4}$$

The results are given as the mean value of a minimum of 15 measurements per sample.

Dielectric properties of woven jute fabrics

Measurement of the dielectric properties was performed on Precise LCR Hameg 8118 instrument, calibrated against Keithley 5155 standards (10^8–10^{13} Ω, voltage coefficient: − 0.03%/V). The instrument was coupled to an LD-3 Rigid Dielectric Cell 3-terminal (guarded), which effective diameter of electrodes was 63.5 mm. The space between the electrodes l (m), which is equal to the thickness of the sample, is controlled by a micrometer on the movable electrode. Dielectric measurements were carried out perpendicular to the samples. Twelve measurements were performed over a frequency region between 30 Hz and 140 kHz, averaged for 90 runs in a single point, using 1.5 V signal. All measurements were carried out in parallel capacitance mode of the instrument at room temperature of 22 °C. Woven jute fabrics were exposed to 30% relative air humidity for 24 h and after that three sets of measurements were done. Acquisition of the conductance, G (S), and susceptance, B (S), as well as the conductance, G_0 (S) and susceptance, B_0 (S) of an empty cell, is carried out with specially programmed software for this measurement. Based on the experimental data, the capacity of the condenser prior to the introduction of the sample, C_0 (F), and after the introduction of the sample, C_s (F), were calculated according to the Eqs. (5) and (6), respectively:

$$C_0 = \frac{\varepsilon_0 \cdot A}{l} \tag{5}$$

$$C_s = \frac{B - B_0 + 2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot A \cdot l^{-1}}{2 \cdot \pi \cdot f} \tag{6}$$

where ε_0 is the permittivity of a vacuum (8.854×10^{-12} F/m), A (m^2) is the area of the electrode, f (Hz) is the frequency.

The effective relative dielectric permeability (ε'_m) was calculated according to Eq. (7):

$$\varepsilon'_m = \frac{C_s}{C_0} \tag{7}$$

The real part of AC specific electrical conductivity (σ_{AC}) was determined using the Eq. (8):

$$\sigma_{AC}\left(\mathrm{Sm}^{-1}\right) = \frac{(G - G_0) \cdot l}{A} \tag{8}$$

where l (m) is the space between electrodes and A (m^2) is the area of the sample.

The dielectric loss tangent (tanδ) was determined using the Eq. (9):

$$\tan\delta = \frac{G - G_0}{B - B_0 + 2\cdot\pi\cdot f\cdot\varepsilon_0\cdot S\cdot l^{-1}} \quad (9)$$

Results and discussion

Chemical composition of woven jute fabrics

In order to study the influence of the alkali treatment severity on the sorption and dielectric properties, woven jute fabric was treated with sodium hydroxide solution of different concentrations for different periods of time. According to the preliminary investigations, appropriate alkali treatment conditions have been chosen to obtain jute fabrics with gradually decreased content of hemicelluloses and unchanged content of lignin, as it can be seen in Table 1.

Observing in parallel the results of the weight loss and content of hemicelluloses, it is clear that the weight loss after the alkali treatments is due to the removal of the hemicelluloses and other non-cellulosic components (fats, waxes and pectin). By the increasing of the alkali treatment severity, i.e. the concentration of NaOH and/or treatment time, the weight loss increases, while the content of hemicelluloses decreases, Table 1. The highest weight loss (12.07%) and the highest removal of hemicelluloses (about 43%) were noticed when the jute fabric was treated with 17.5% NaOH for 30 min (sample H30/17.5). The differences in the weight loss and content of hemicelluloses are about 16.6% and 10.5%, respectively, when the jute fabrics were treated with the same concentration of NaOH during a different time (samples H5/17.5 and H30/17.5). These results for woven jute fabrics treated with different concentrations of NaOH during the same time are about 105.6% and 33.7%, (samples H30/1 and H30/17.5) and about 20.0% and 13.4% (samples H5/10 and H5/17.5), respectively. From the given results, it is clear that the concentration of NaOH has a higher influence on the weight loss and content of hemicelluloses in relation to the treatment time.

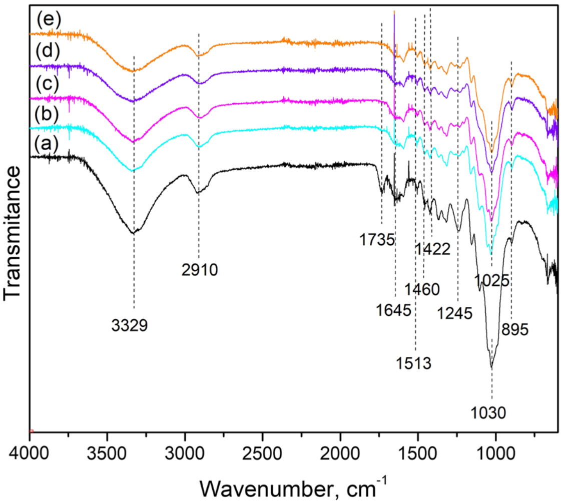


Fig. 1 ATR-FTIR spectra of (a) untreated and alkali treated (b) H30/1, (c) H5/10, (d) H5/17.5 and (e) H30/17.5 woven jute fabrics

The above mentioned changes in the chemical composition were confirmed by ATR-FTIR spectra, Fig. 1. Strong peaks at 1735 cm^{-1} (Lazic et al. 2018; Ray and Sarkar 2001) and 1245 cm^{-1} (Mwaikambo and Ansell 2002) which originate from C=O stretching vibration of the carboxylic acid or ester groups present in the hemicelluloses were noticed in the spectrum of untreated woven jute fabric. After the alkali treatments, the decreased intensity of these peaks proved partial removal of the hemicelluloses. Similar observations have also been made by other researchers for alkali treated hemp and sisal fibers (Mwaikambo and Ansell 2002). The alkali treated jute fabrics have a higher content of α-cellulose, as a direct consequence of the decreased content of hemicelluloses, Table 1. The peak at 895 cm^{-1} which occurs in the spectra of both the untreated and alkali treated jute fabrics indicates the presence of the β-glycosidic linkages between the glycosidic units (Mwaikambo and Ansell 2002). The peaks at 1513 cm^{-1} and 1460 cm^{-1} (Ahuja et al. 2017) representing the aromatic ring C=C of the phenylpropane group of the lignin and peak at 1422 cm^{-1} (Zhang et al. 2015) corresponding to the aromatic skeletal vibrations and ring breathing with C–O stretching in lignin, occurred in the untreated and alkali treated jute fabrics, imply that lignin exists still in alkali treated jute fabrics, while unchanged peaks intensity suggests that the lignin remains unimpaired after the alkali treatments, Fig. 1 and Table 1. This is due to its aromatic nature, as well as the presence of strong carbon–carbon linkages, which are very resistant to degradation or fragmentation (Kostic et al. 2008; Pejic et al. 2008; Wang et al. 2003).

It is good to mention some other peaks which can be perceived on the ATR-FTIR spectra. They are mainly assigned to polysaccharides, especially cellulose and belong to the fingerprint region, such as those at 1336, 1318, 1162 and 1110 cm^{-1} (Lazic et al. 2018). Furthermore, the peak at 1030 cm^{-1} for the untreated woven jute fabric and the peak at 1025 cm^{-1} (Fig. 1) for the alkali treated jute fabrics are characterized as the C–O stretching bond structure of alcohols functional group (Bakri et al. 2016). The small peak with maxima at 2910 cm^{-1} (Fig. 1) in the region of the C–H stretching bond structure includes the functional groups of methyl (CH_3), methylene (CH_2) and aliphatic saturated (CH), which originated from the cellulose and hemicelluloses (Lazic et al. 2018), as well as from the lignin (Bakri et al. 2016). This adsorption band decreased slightly after the alkali treatments due to the breaking of the hydrogen bonds between the –OH groups of the cellulose and the hemicelluloses molecules. The peak at 1645 cm^{-1} (Fig. 1) does not belong to the fiber, however, its presence can be attributed to the H–O–H stretching vibration of the absorbed water (Lazic et al. 2018).

Structural characteristics and air permeability of woven jute fabrics

The effects of the alkali treatment severity on woven jute fabric structural characteristics and air permeability can be clearly seen in Table 2. The alkali treatments were done in slack conditions, which resulted in the fiber swelling and contraction of their length, which contributed to shrinkage in length and width of the fabrics. It is found that with increasing severity of the alkali treatment (concentration of NaOH, and/or treatment time), the yarn density in fabric, fabric thickness and fabric weight were increased, while the porosity and air permeability decreased. For example, after 5 min treatment with 17.5% NaOH (sample H5/17.5) warp and a weft yarn density in the fabric increased for about 37% and 45.5%, respectively in comparison with the untreated jute fabric. Usually, the shrinkage in length and width of the fabrics causes an increase of the fabrics thickness and fabric weight. For the previously mentioned sample (H5/17.5), after the alkali treatment, the fabric thickness increased for about 133%, while the fabric weight increased for about 86%. Such significant changes in the structural characteristics are a consequence of the previously mentioned lateral swelling, which occurs together with considerable shrinkage in length, but also the higher degree of crimp developed during the alkali treatment under severe conditions (Ray et al. 1983). Increased yarn density in fabric, fabric thickness and fabric weight mean decreased space between the yarns, and thus decreased porosity and air permeability of the fabric. In other words, the values of porosity are consistent with the values of air permeability, i.e. the higher the value of porosity of the fabric, the higher is the value of air permeability and vice versa (Asanovic et al. 2015). The regression analysis shows a very high coefficient of linear correlation between the fabric porosity and air permeability (r = 0.989).

Sorption properties of woven jute fabrics

As it was expected, the chemical composition, in our case, the content of hemicelluloses, has an impact on the various sorption properties, which were evaluated

Table 2 Structural characteristics and air permeability of untreated and alkali treated woven jute fabrics

Sample code	Yarn density in fabric (cm^{-1})		Diameter of yarn (cm)		Fabric thickness (mm)	Fabric weight (gm^{-2})	Fabric porosity (%)	Air permeability (lm^{-2}s^{-1})
	Warp	Weft	Warp	Weft				
C	4.6	4.6	0.0420	0.0530	0.762	266	61.0	2860
H30/1	5.0	5.2	0.0540	0.0552	1.274	313	52.1	2564
H5/10	5.5	6.0	0.0595	0.0748	1.513	392	37.1	2104
H5/17.5	6.3	6.7	0.0685	0.0721	1.773	495	29.4	1570
H30/17.5	6.4	6.7	0.0744	0.0762	1.868	529	25.6	1518

by determination of moisture sorption (MS), water retention power (WRP) and degree of fiber swelling (DS) in distilled water. The moisture sorption values and degree of fiber swelling provide information about the degree of accessibility of the cell wall components to water vapor (Pejic et al. 2008) and an aqueous solution (Pejic et al. 2009) within the fiber, respectively. On the other hand, the water retention power represents the total water holding capacity of all water absorbing and holding surfaces, cavities and cracks in the jute fiber structure (Kostic et al. 2008; Lazic et al. 2018; Pejic et al. 2009).

Due to the presence of free hydroxyl groups, i.e. active chemical groups important for moisture absorption in the jute amorphous regions and at crystallite's surface (Kostic et al. 2010; Lazic et al. 2018), the moisture sorption of untreated jute fabric is high (7.41%). In comparison with the untreated, the alkali treated woven jute fabrics have a higher ability for moisture sorption (Table 3 and Suppl. Fig. S2), which can be described as higher availability of the hydroxyl groups, which occurs as a result of removal of the hemicelluloses and earlier mentioned fiber swelling due to the alkali treatments under slack conditions. Furthermore, the effect of the conversion from cellulose I to more accessible cellulose II polymorph (at NaOH concentration $\geq$ 10%) (Suppl. Fig. S1) should not be neglected; a detailed discussion is given in the supplementary material. The relationship between the content of hemicelluloses and moisture sorption measured at different relative air humidity (30% and 65%) is given in Table 3 and Suppl. Figs. S2 and S3. In this part, only the results for the moisture sorption at 65% relative air humidity will be discussed. The highest moisture sorption (9.38%) was obtained for the sample H30/17.5 with the lowest hemicelluloses content (Table 1) and the highest conversion from cellulose I to cellulose II, Suppl. Fig. S1. With decreasing the content of hemicelluloses for about 14.4, 26.8, 36.6 and 43.3% for H30/1, H5/10, H5/17.5, H30/17.5 samples, the moisture sorption increased for about 16.7, 17.5, 21.6 and 26.6%, respectively. These results are comparable with the results obtained for chemically modified hemp fibers with NaOH solution of different concentrations (Pejic et al. 2008). The FTIR spectra (Fig. 1) also confirm these results. All jute fabrics show strong band within the range 3600–3000 cm^{-1} (Fig. 1), commonly related to the absorption by hydroxyl groups (Islam et al. 2011; Ray and Sarkar 2001). This band was found to broaden for the alkali treated jute fabrics, supporting the possibility of increased availability of the hydroxyl groups (Islam et al. 2011).

The jute fibers are hygroscopic with high affinity to water, and water retention power is a very important indicator of their sorption properties. Thus, through adsorption and absorption into the non-crystalline portion of the cellulose and all non-cellulosic components, the water comes into contact with a very large surface area of different cell wall components (Pejic et al. 2009). The regression analysis shows very high coefficients of linear correlation between the content of hemicelluloses and water retention power (r = – 0.994), Suppl. Fig. S4. For example, the removal of 43.3% of hemicelluloses (sample H30/17.5) results in 48.8% higher water retention power by the alkali treated jute fabric compared to the untreated. The observed change can be explained by the effective removal of hemicelluloses, as well as a hydrophobic layer from the fiber surfaces and changes in the fiber

Table 3 Relationship between the content of hemicelluloses and sorption properties of woven jute fabrics

Sample code	Content of hemicelluloses (%)	Moisture sorption at 65% air humidity (%)	Moisture sorption at 30% air humidity (%)	Water retention power (%)
C	21.76	7.41	6.50	57.23
H30/1	18.62	8.65	6.97	69.35
H5/10	15.93	8.71	7.07	74.76
H5/17.5	13.79	9.01	7.51	81.84
H30/17.5	12.34	9.38	7.87	85.16

structure (i.e. size and a number of pores and microcracks) (Lazic et al. 2018). The removal of hemicelluloses and hydrophobic layer improve the hydrophilicity of jute fabrics.

The higher water retention power of the alkali treated woven jute fabrics is not just a consequence of the changes in the content of hemicelluloses and fiber structure, but also is a consequence of the higher degree of fiber swelling in water. The interaction between the jute fibers and water can be explained as a competition of hydrogen-bonds formation between the hydroxyl groups of the polymer (mainly cellulose, but also non-cellulosic components like hemicelluloses and lignin) and water molecules or water clusters. The water penetrates inside the fiber and breaks the secondary interactions between the cellulose macromolecules and after that, it is adsorbed into the fiber by hydrogen bonds, which cause swelling of the fiber. From the data presented in Fig. 2 and Table 1, it is evident that the degree of swelling of all alkali treated jute fibers increased with decreasing the content of hemicelluloses. By partial removal of the hemicelluloses during the alkali treatments, the interfibrillar regions become less dense and less rigid, which together with the higher content of amorphous regions enable easier penetration of higher amount of water molecules into a jute fiber structure, and its higher swelling (Kostic et al. 2010). Similar observations were made by Pejic et al. (2009) for alkali modified hemp fibers. As in there, so in our case, the most intensive swelling has occurred in the first 5 min. Namely, after 5 min of immersing in water, the swelling of the alkali treated jute fibers increased for 12.5, 21.7, 28.0 and 49.6% for H30/1, H5/10, H5/17.5 and H30/17.5 samples respectively, in comparison with the untreated jute fabric, according to Fig. 2. The jute fibers continue to swell, achieving a maximum degree of swelling after 30 min; with prolonged observation, only negligible changes in fiber diameter have occurred.

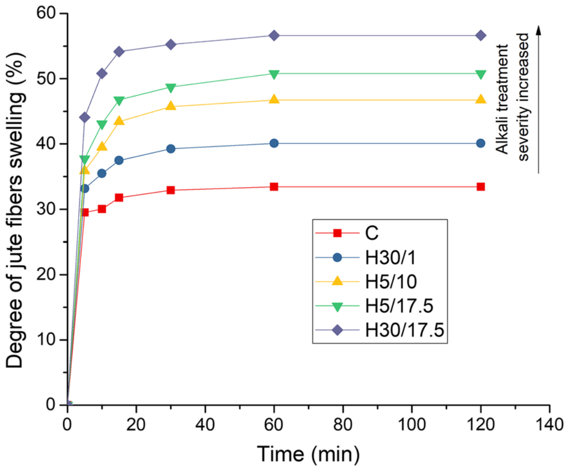


Fig. 2 A degree of jute fiber swelling

The improved sorption properties of alkali treated jute fabrics can be associated by the location of the hemicelluloses in the jute fiber structure. As a low molecular weight cellulosic fraction, hemicelluloses occupy the space between the fibrils in both the primary and secondary walls of the jute fibers. The decreased content of hemicelluloses in these areas, after the alkali treatments, leads to less dense interfibrillar regions, making the fibrils capable for spacious rearrangement (Lazic et al. 2018). Thus, it is possible to create new free spaces in the fiber structure, which is followed by pronounced liberation of the elementary fibers and partial peeling of fiber surface, as it can be seen in Fig. 3b–e. In the sample H5/10 (Fig. 3c), the cementing material from the matrix was removed to some extent and the individual elementary fibers became more prominent. Increased intensity of the alkali treatment (sample H30/17.5, Fig. 3e) leads to intensive removal of the cementing materials, which results in better separation of the elementary fibers and clearly visible fibrillar structure. The alkali treatments lead to a relatively cleaner surface (Fig. 3b–e) which indicates the removal of the hemicelluloses and other non-cellulosic components (fats, waxes and pectin), as it was confirmed by the analysis of the chemical composition and FTIR spectra (Table 1 and Fig. 1). In contrast, the untreated jute fibers (Fig. 3a) still seem to be joined together into bundles by non-cellulosic components. The obtained SEM photographs are similar with those obtained for alkali treated jute (Ray and Sarkar 2001), flax (Lazic et al. 2018), kenaf (Kargarzadeh et al. 2012) and sisal (Mwaikambo and Ansell 2002) fibers.

Dielectric properties of woven jute fabrics

In this section, the various factors that affecting the dielectric properties of fabrics, which according to Bal and Kothari (2009) are classified into two groups, i.e. external and internal factors, will be discussed. External factors are the conditions under which the

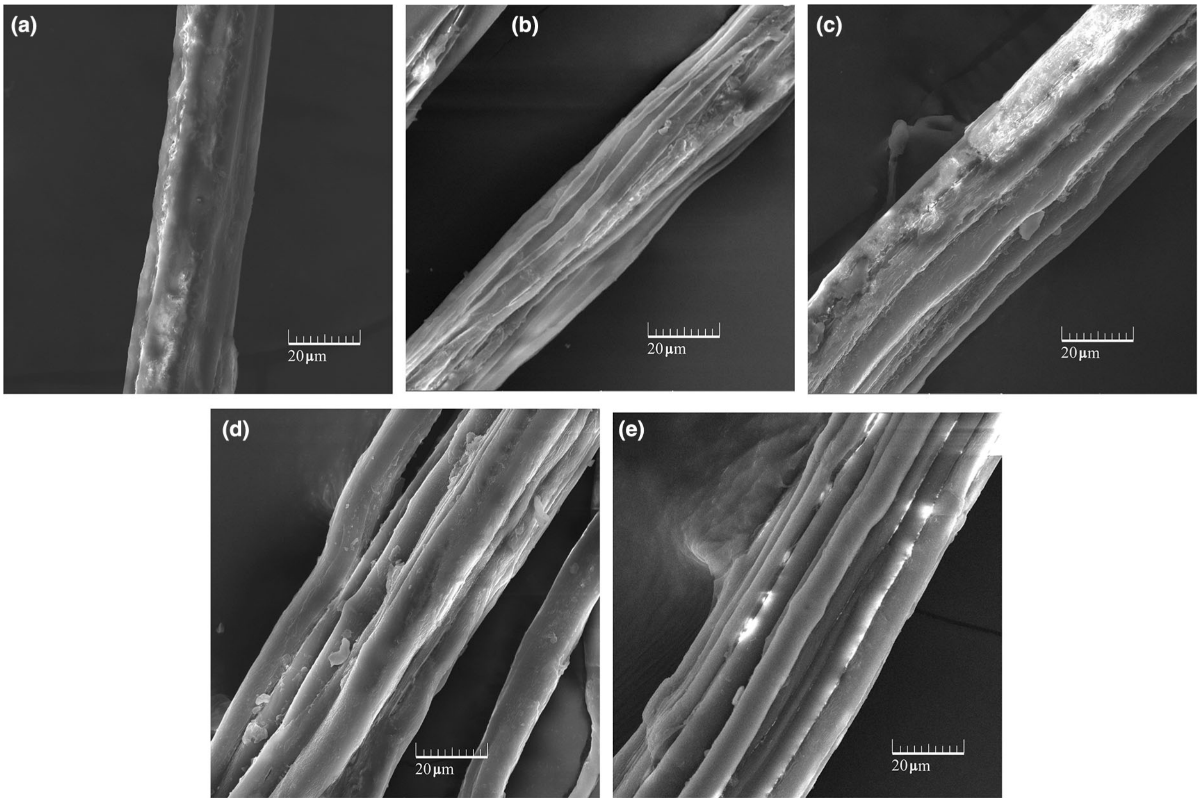


Fig. 3 SEM photographs of **a** untreated fiber, alkali treated jute fibers: **b** H30/1, **c** H5/10, **d** H5/17.5 and **e** H30/17.5

measurement is done, such as frequency, air humidity and temperature. Internal factors are those which are decided by the sample itself, such as chemical composition, moisture sorption and structural characteristics.

The results obtained for the dielectric properties of alkali treated woven jute fabrics, measured in the frequency region between 30 Hz and 140 kHz at 30% relative humidity, are presented in Figs. 4, 5 and 6. Since the fabric is a heterogeneous three-phase system, it was suggested to refer it as the capacitance of the "fiber–moisture–air" system (Bal and Kothari 2009). In that context, the dielectric properties such as effective relative dielectric permeability, AC specific electrical conductivity and dielectric loss tangent are very sensitive to fabric's chemical composition, moisture sorption and structural characteristics. The effective relative dielectric permeability of the material describes its polarization (dipole rotation and dipole distribution), while the dielectric loss tangent, also known as "dissipation factor" represents the energy loses occurring due to the motion or rotation of the atoms or molecules within the dielectric (Cerović et al. 2014).

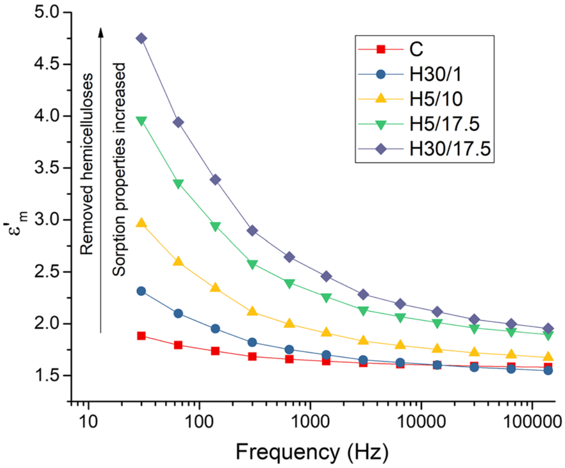


Fig. 4 The frequency dependence of the effective relative dielectric permeability (ε'_m) of woven jute fabrics

The frequency dependence of the effective relative dielectric permeability (ε'_m) of untreated and alkali

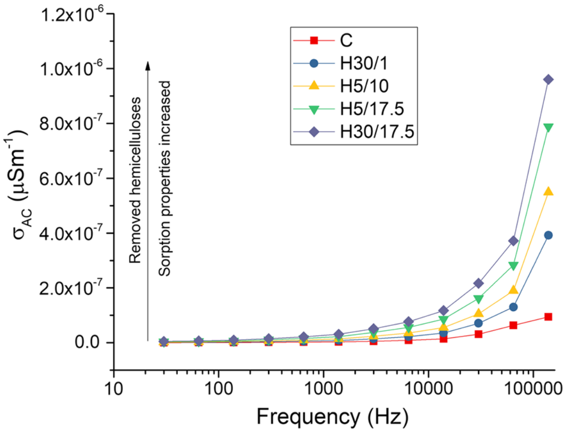


Fig. 5 The frequency dependence of the AC specific electrical conductivity (σ_{AC}) of woven jute fabrics

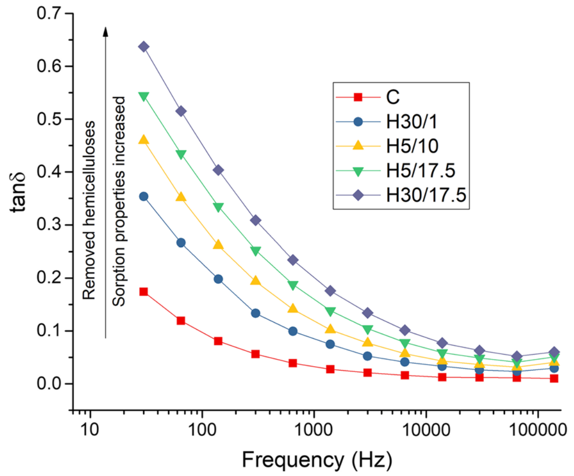


Fig. 6 The frequency dependence of the dielectric loss tangent (tanδ) of woven jute fabrics

treated woven jute fabrics is shown in Fig. 4. For all jute fabrics, the highest values of ε'_m were noticed at the lowest measured frequency (30 Hz). After a strong decrease of the ε'_m with an increase of the frequency (between 30 Hz and 3 kHz), the ε'_m slightly changed in the frequency region higher than 3 kHz. The observed decrease of the ε'_m with the increase in frequency can be explained by the fact that when the frequency increases, dipoles have less time to orient themselves in the direction of the alternating field, which will lead to a low polarization (Cowie and Arrighi 2008; Asanovic et al. 2018). The obtained results are in accordance with the results obtained for ε'_m of lignocellulosic composites (Markiewicz et al. 2009), woven fabrics of flax, hemp, and cotton (Cerovic et al. 2009) and woven cotton fabric (Cerovic et al. 2013). Bearing in mind the fact that the ε'_m refers to a fiber-moisture-air system, the obtained increases of the ε'_m after the alkali treatments can be attributed to the changes in the structural characteristics, as well as the decrease of the content of hemicelluloses, which further increase the ability for moisture sorption. As we mentioned earlier, the higher availability of the cellulose hydroxyl groups, which occurs as a result of the hemicelluloses removal, contributed to higher moisture sorption of the alkali treated jute fabrics in comparison with the untreated. When such porous fabrics contain moisture, the discussion about their ε'_m becomes even more challenging. Comparative analysis of the results presented in Tables 1 and 2 and in Figs. 2 and 4, shows that untreated jute fabric (sample C) which has the highest porosity (61.0%) and content of hemicelluloses (21.76%) and the lowest moisture sorption (6.52%) has the lowest, while the jute fabric treated under the most severe conditions (sample H30/17.5), which is characterized by the lowest porosity (25.6%) and content of hemicelluloses (12.34%) and the highest moisture sorption (7.87%), has the highest ε'_m. Asanovic et al. (2018) came to the same relationship between the sorption properties and ε'_m of viscose/polypropylene nonwoven fabrics. George et al. (2013) and Markiewicz et al. (2009) investigated the dielectric properties of lignocellulosic composites and concluded that the ε'_m increased with the increase of the content of lignocellulosic fibers, which contributed to higher moisture sorption. Even more, Fraga et al. (2006) used dielectric properties to observe water uptake in the natural fiber-based composites.

The obtained results for effective relative dielectric permeability of the examined woven jute fabrics correspond with the results obtained for AC specific electrical conductivity. Figure 5 presents the frequency dependence of the AC specific electrical conductivity (σ_{AC}) of the investigated jute fabrics. The polarization of the electrode was manifested through the occurrence of a plateau in the frequency region between 30 Hz and 1 kHz. The values of the fabrics σ_{AC} increases with the increase of the frequency and the differences between them are higher at higher frequencies. The lowest σ_{AC} was noticed for the untreated jute fabric, which can be related to its lowest fabric thickness and fabric weight, as well as the highest porosity, Table 2. The changes of the structural characteristics as a consequence of the previously mentioned hemicelluloses removal and lateral swelling, which occurs together with considerable shrinkage in length during the alkali treatments under severe conditions, affect the σ_{AC}. For example, 2.3 times higher fabric thickness, 1.9 times higher fabric weight and 2.1 times lower porosity of the sample H5/17.5, compared to the untreated fabric, resulted in 8.2 times higher σ_{AC} (at around 140 kHz). Furthermore, this sample has 36.6% lower content of hemicelluloses as well as 15.5% higher moisture sorption in comparison with the untreated fabric, which has also contributed to the higher σ_{AC}. According to the literature data (Saukkonen et al. 2015), such changes can be explained by the fact that hemicelluloses not only restrict the freedom of the water molecules to take part in the polarization process but also change the structure in such a way that the mobility of the ions in the electric field is restricted. On the other hand, Bal and Kothari (2009) and Asanovic et al. (2018), the increased σ_{AC} explained by the presence of water in form of moisture, leading to increase the number of the polar groups, which facilitate the flow of current through amorphous regions, as well as the crystallite's surface.

Having in mind the effect of the structural characteristics, the content of hemicelluloses and moisture sorption on the effective relative dielectric permeability and AC specific electrical conductivity, we decided to investigate the dielectric loss tangent (tanδ) as a function of these parameters. The lowest value of tanδ (Fig. 6) in the frequency region between 30 and 100 Hz for the untreated woven jute fabric can be explained by the orientation polarization of cellulose, hemicelluloses, and lignin molecules, or by the interfacial polarization at the boundary between the crystalline and amorphous regions of the cellulose (Kabir et al. 2001). The tanδ increased further as the content of hemicelluloses decreased due to the increase in the number of polar groups. As a result of the higher number of polar groups, the orientation polarization at lower frequencies increases leading to a higher tanδ values. With decreasing the content of hemicelluloses from 21.76 (sample C) to 18.62, 15.93, 13.79 and 12.34% for H30/1, H5/10, H5/17.5, H30/17.5 samples, the tanδ (at 30 Hz) increased from 0.174 (sample C) to 0.354, 0.459, 0.545 and 0.637, respectively. Such behavior can be explained by the weaker interaction of the dipole structures with the participation of the hemicelluloses, as it was reported for the paper having different content of hemicelluloses (Saukkonen et al. 2015). At frequencies higher than 100 Hz, the orientation polarization of the polar groups does not take place completely and hence, the tanδ decreased with increasing frequency.

Since the fabric structural characteristics were changed depending on severity of the alkali treatments (Table 2), the influence of fabric structure on the tanδ should not be neglected. Cerovic et al. (2009, 2014) established the relationship between the dielectric properties, structural characteristics and air permeability of woven fabrics made of flax, hemp, jute, cotton, etc. (Cerovic et al. 2009), and woven PET fabric (Cerović et al. 2014). In our case, higher values of tanδ were obtained for jute fabrics with higher yarn density in fabric, fabric thickness and fabric weight, and lower porosity and air permeability. For example, when the jute fabric was treated at milder conditions (sample H30/1), the yarn density in fabric increased for 8.7% (warp direction) and for 13.0% (weft direction), fabric thickness for 67.2%, fabric weight for 47.4%, while the fabric porosity and air permeability decreased for 14.6% and 10.4%, respectively. These changes in the structure and air permeability lead to increase of the tanδ for 3.1 times (at 30 Hz).

The results of this investigation confirm the influence of the internal factors, such as chemical composition, moisture sorption and structural characteristics on the dielectric properties of alkali treated jute fabrics. According to Bal and Kothari (2009), which suggested referring the fabric as the capacitance of "fiber–moisture–air" system, from the results it can be concluded that jute fabrics with improved dielectric properties can be obtained with increasing alkali treatment severity, i.e. when the content of hemicelluloses and fabric porosity decreased, while the moisture sorption, fabric thickness and fabric weight increased.

Conclusion

The present investigation shows the influence of the alkali treatment conditions on the chemical composition, structural characteristics, sorption and dielectric properties of woven jute fabrics. Jute fabrics with different structural characteristics, as well as gradually decreased content of hemicelluloses (from 21.76%

down to 12.34%), were obtained by choosing appropriate alkali treatment conditions. The analysis of the obtained results showed that the decreased content of hemicelluloses increased the accessibility of the cell wall components to water vapor and the total water holding capacity of fabrics, which lead to the increase in the moisture sorption, water retention power and degree of fiber swelling. Furthermore, the alkali treatments affect jute fabrics structural characteristics. Namely, the alkali treated jute fabrics have higher yarn density in fabric, fabric thickness and fabric weight, and lower porosity and air permeability. The obtained SEM photographs showed that the alkali treatments result in liberation of the elementary fibers and relatively cleaner fiber surface. Furthermore, the detailed dielectric spectroscopic investigations of the alkali treated woven jute fabrics indicate that the higher fabric thickness, fabric weight and moisture sorption as well as lower porosity and decreased content of hemicelluloses contributed to higher values of dielectric properties, such as effective relative dielectric permeability, AC electrical conductivities and dielectric loss tangent. The results of our research are a confirmation of the fact that the investigated dielectric properties can be successfully used as an indirect indicator for the moisture sorption ability, but also as a possible indirect indicator for the content of hemicelluloses in jute fabrics. Furthermore, the obtained results can be used to select the alkali treatment conditions in order to obtain jute fabrics with desired sorption and dielectric properties, depending on their end use.

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