Fibers and Polymers 2020, Vol.21, No.10, 2407-2416
DOI 10.1007/s12221-020-1340-4

ISSN 1229-9197 (print version)
ISSN 1875-0052 (electronic version)

Multipurpose Nonwoven Viscose/Polypropylene Fabrics: Effect of Fabric Characteristics and Humidity Conditions on the Volume Electrical Resistivity and Dielectric Loss Tangent

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(Received December 10, 2019; Revised January 15, 2020; Accepted February 5, 2020)

Abstract: In this work, the volume electrical resistivity and dielectric loss tangent of viscose/polypropylene multipurpose nonwoven fabrics were examined. According to the obtained results, the changes in the volume electrical resistivity depend on the applied chemical bonding agent, viscose fiber content, moisture content, fabric thickness, fabric weight, and relative air humidity. Based on the volume electrical resistivity hysteresis, the portion of sorbed moisture retained in the material after desorption, as well as the portion of moisture removed from the material during desorption, were determined. Furthermore, the dielectric loss tangent measured at the frequency range between 30 Hz and 140 kHz, for the samples exposed to different relative air humidity (40 % and 80 %) and wet samples, is dependent on the chemical bonding agent, viscose fiber content, moisture content, as well as frequency of the external electric field. The dielectric loss tangent measured at 80 % relative air humidity showed a peak at about 100 Hz, while for the wet samples, the peak was observed in the frequency range between 30 and 140 kHz. In a wet state, the dielectric loss tangent is primarily influenced by the water molecules present in the sample.

Keywords: Multipurpose nonwoven fabrics, Viscose/polypropylene, Volume electrical resistivity, Dielectric loss tangent, Humidity conditions

Introduction

The nonwoven fabrics are widely used as a multipurpose cleaning cloth thanks to their versatility and exceptional properties such as high water absorption and water retention, high cleaning efficiency in dry or wet conditions, good hygienic characteristics, large free inner volume, etc. [1,2]. In addition, the nonwoven fabrics should also possess a low propensity to generate static electricity, i.e. satisfied electro-physical properties in order to be suitable for use as a multipurpose cleaning cloth [2]. Besides measuring the amount of static electricity on the textile materials, determination of other electro-physical properties such as electrical resistance (volume and surface resistance) and dielectric properties (effective dielectric permeability, electrical conductivity, and dielectric loss tangent) can also be used as indirect indicators of the tendency of the textile materials to generate static electricity [2,3].

From the literature survey, it is evident that a large number of studies are dedicated to determine the electrical resistance and dielectric properties of textile materials in the form of nonwoven [2,4-7], woven [3,8-14], knitted fabrics [15,16], and fiber based composites [17-20]. These studies have shown that the electrical resistance and dielectric properties are closely related to the internal factors such as raw material composition, i.e. the fiber type, content of amorphous and crystalline regions in the fiber, type of fabric, structural characteristics of fabrics, moisture content of the material, etc., and external factors such as the ambient air humidity and temperature [2-21]. The dielectric properties also depend on the frequency of the applied alternating electric field [2-5,12-14,17-21]. Moreover, the chemical treatments of the textile materials such as alkali treatment with sodium hydroxide [14,18], treatment with $KMnO_4$, maleic anhydride modified polypropylene, toluene diisocyanate and stearic acid [17] or treatment with a polymer matrix of chitosan gel with addition of gentamicin sulfate or autochthonous essential oil of Picea abies [15] lead to change their electro-physical properties.

George *et al.* [17] found that the volume resistivity of polypropylene and jute yarns commingled composites decreased with increasing the jute fiber content. In research [16], Wang *et al.*, have shown that the electrical resistance of the cotton and polyester knitted fabric is positively and linearly related to the reciprocal value of moisture regain and that the electrical resistance of fabrics is exponentially related to the electrolyte concentration. Furthermore, George *et al.* [17] found that the dielectric properties (dielectric constant, loss factor and conductivity) of polypropylene and jute yarns commingled composites increased with increasing the jute fiber content due to the better net orientational

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polarization in jute yarns reinforced polypropylene comingled composites. The same conclusion was made by Jayamani *et al.* [18] studying the dielectric properties (dielectric constant, dissipation factor and dielectric loss factor) of jute/ bamboo natural fibers reinforced with polypropylene and unsaturated polyester hybrid composites, and by Li *et al.* [19] investigating the dielectric constant and the loss tangent of kenaf fiber-filled polyurethane foams. Additional chemical treatments (with $KMnO_4$, maleic anhydride modified polypropylene, toluene diisocyanate and stearic acid [17] and sodium hydroxide [18]) lead to a reduction in dielectric constant values due to a reduction in the hydrophilic nature of jute yarns and jute and bamboo fibers, respectively. Also, it was shown that the dielectric loss tangent decreased as the frequency increased for polypropylene-based fabrics [12] and kenaf fiber filled polyurethane foams sample [19] for which the effect of frequency on the loss tangent value was greater at frequencies below 10^2 Hz [19]. Various authors obtained much higher dielectric constant and conductivity value [17], and effective dielectric permeability and AC specific electrical conductivity [2] for wet samples compared to their dry counterparts.

As it was mentioned above, the moisture content showed a significant impact on the electro-physical properties of textile materials. The textile materials absorb different amount of moisture from the surrounding environment, depending on their structural characteristics (raw material composition, fabric thickness and weight, etc.) and ambient air humidity in which they are located. In addition, as the air water molecules are partially ionized, the water around the textile material neutralizes the electric charge on its surface [22]. In general, the fibers with higher moisture content exhibit lower electrical resistance, higher electrical conductivity, effective dielectric permeability and dielectric loss tangent, and their tendency to accumulate static electricity is lower. Therefore, the hydrophilic fibers, such as cellulose, do not tend to accumulate static electricity, while the hydrophobic fibers such as polypropylene and polyester are very prone to do that [7].

Among cellulose fibers, the viscose fibers are a very suitable raw material for producing multipurpose cleaning cloth [2] because they possess good hygienic properties, super water absorbency, softness [2,23], lower electrical resistance [9,10,21], and higher value of dielectric properties [21]. However, in order to increase the strength of the products obtained from viscose fibers, specially in a wet state, they are blended with other fibers, such as polypropylene, polyester, etc. [2]. On the other hand, the addition of hydrophobic fibers, such as polypropylene, which is characterized by the high electrical resistance value [24] and low values of dielectric properties [12], influences the electro-physical properties of nonwoven materials.

In that context, the aim of this work was to investigate the influence of relative air humidity on the volume electrical resistivity and dielectric loss tangent of polypropylene/ viscose nonwoven fabrics (with different viscose fiber content, thickness, fabric weight, and with and without chemical bonding agent) intended for multipurpose cleaning cloth. Bearing in mind the fact that the multipurpose cleaning cloths are used not only in dry conditions (usual relative air humidity in the rooms) but also in wet conditions (by their immersion in water), the dielectric loss tangent measurement was also conducted in a wet state. The obtained results would allow selecting the appropriate samples depending on the end use conditions (dry or wet). In addition, the purpose of this work was to show that the volume electrical resistivity and dielectric loss tangent measurements can be used for monitoring the tendency of nonwoven fabrics to moisture sorption and monitoring the volume electrical resistivity for moisture desorption.

Experimental

Materials

The basic structural characteristics and moisture content of the investigated commercially produced multipurpose nonwoven cleaning cloths are given in Table 1.

Methods

Determination of the Morphology and Surface Chemistry of the Samples

The nonwoven fabric surface morphology was assessed by Scanning Electron Microscope (SEM JEOL 840A). The fiber distribution in the investigated fabrics is related to the machine direction (MD).

The surface chemistry of the fabrics was characterized using Attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR). The transmission spectra were obtained using Shimadzu IRAffinity-1 (FT-IR) spectro-photometer 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

Table 1. Structural characteristics and moisture content of the investigated nonwoven fabrics

Sample	Material composition	Fabric weight ($g \cdot m^{-2}$)	Fabric thickness (mm)	Moisture content (%)	
				At 40 % air humidity	At 80 % air humidity
1	Viscose/polypropylene (66/34 %)	104	0.95	6.65	11.44
2	Viscose/polypropylene (80/20 %)	159	1.17	8.15	12.79
3	Viscose/polypropylene (73/27 %)	239	1.95	7.83	10.96

2 cm^{-1} and in 20 scan mode [14].

Determination of the Structural Characteristics and Moisture Sorption

The weight (i.e. mass per unit area) of the nonwoven fabrics was determined according to the standard ISO 9073-1 [25]. The fabric thickness was measured at a pressure of 9.81 kPa using a thickness tester (AMES, type 414-10, USA) [2]. The average of ten measurements for each sample was considered.

The moisture content was measured according to the thermo-gravimetric method using Infrared Moisture Analyzer (Sartorius MA35). Before measurements, the samples were exposed to different relative air humidity (40 % and 80 %) for 24 hours. The average of three measurements for each sample was considered [2].

Determination of Electro-physical Properties

The dc volume electrical resistance was determined with the device developed at the Department of Textile Engineering of the Faculty of Technology and Metallurgy at the University of Belgrade. That device was successfully used for determining volume electrical resistance of hemp fibers [22], yarns with different chemical composition [9,26], nonwoven [4], woven [9-11] and knitted fabrics [15]. The measurement of dc volume electrical resistance was performed using the voltage method that has been presented in some papers [10,11,15,22]. The dc volume electrical resistance of the investigated nonwoven fabrics was determined in the machine direction (MD) and cross direction (CD).

For each sample, two measurements were conducted, whereby during each measurement three specimens of nonwoven fabric were connected to electrodes. In this way, the total resistance is lower, the sensitivity of the method increases and the results are more accurate, comparing to those results obtained for separate specimen measurement [26].

On the basis of the determined dc volume electrical resistance of nonwoven fabrics (R_x), the dc volume electrical resistivity ρ (GΩcm), which quantifies how strongly that fabric opposes the flow of the electric current, is calculated according to the following equation [10,11,15]:

$$\rho = \frac{R_x \cdot S_F}{l} \tag{1}$$

where, R_x is measured volume electrical resistance (GΩ), S_F is surface of the sample cross section (cm^2) and l is length of sample i.e. length between electrodes (1 cm). Samples' cross section S_F is calculated by multiplying the thickness of the sample (given in Table 1) and their width.

The measurement was performed through increasing the relative air humidity (in further text humidity) in the chamber (from 35 % to 58 %). After attaining 58 % humidity, the humidity in the chamber decreased down to the starting value of 35 %. All measurements were performed at room temperature (22±2 °C).

The energy losses occurring due to the motion or rotation of the atoms or molecules within the dielectric were expressed by the dielectric loss tangent value (tan δ). Dielectric Cell 3-terminal (guarded) was used for determination of dielectric loss tangent at room temperature of 22 ºC. The effective diameter of the cell electrodes was 63.5 mm and the measurements were carried out perpendicular to the samples. Three sets of measurements were done for samples exposed for 24 hours to 40 % and 80 % humidity and for wet samples. Wet samples were prepared for measurement by immersion in distilled water for 60 s. After that, they were dried at room temperature for 120 s before measurement. The values of conductance, G (S), and susceptance, B (S), as well as, the conductance, G_b (S), and susceptance, B_b (S) of an empty cell with space between electrodes equal to the thickness of the sample, are registered at twelve frequencies over a frequency range from 30 Hz to 140 kHz in parallel capacitance mode of the instrument using 1.5 V signal. Based on the recorded values, tan δ was calculated according to the following equation [14]:

$$\tan\delta = \frac{G - G_b}{B - B_b + 2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot S \cdot l^{-1}} \tag{2}$$

where, f (Hz) is the frequency, ε_0 (ε_0=8.85·10^{-12} F·m^{-1}) is the permittivity of a vacuum, l (m) is space between electrodes which is equal to the sample thickness, and S (m^2) is the area of the sample under electrode.

Results and Discussion

Morphology and Surface Chemistry of the Investigated Samples

Figure 1 shows a surface morphology of the viscose/

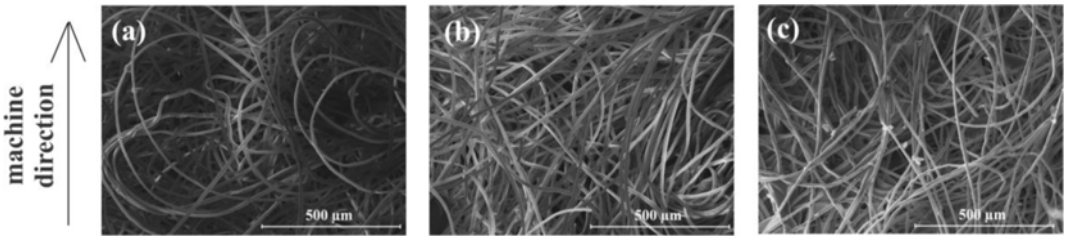

Figure 1. SEM microphotographs of the; (a) Sample 1, (b) Sample 2, and (c) Sample 3.

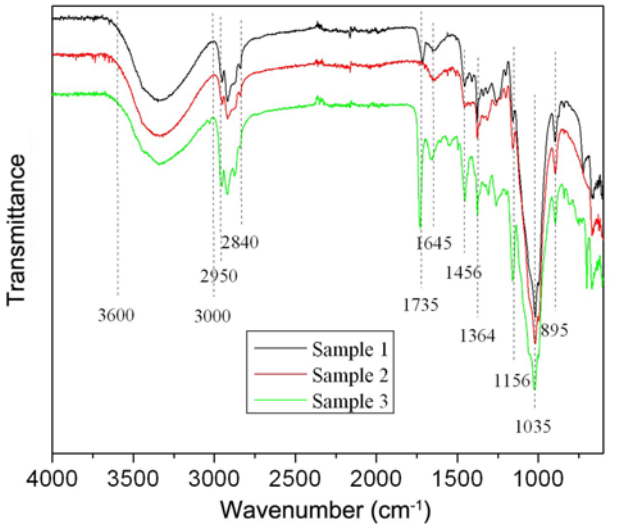

Figure 2. ATR-FTIR spectra of the viscose/polypropylene nonwoven fabrics.

polypropylene nonwoven fabrics. As it can be seen, SEM microphotograph of Sample 3 (Figure 1c) displays the presence of chemical bonding agent distributed in the form of segments of the binding film over the surface and in the bulk of the nonwoven fabric.

The presence of chemical bonding agent in Sample 3 can be additionally confirmed by the existence of a strong peak at 1735 cm^{-1} in its FTIR spectrum (Figure 2), which originates from C=O stretching in unconjugated ketones, carbonyls or esters [27-29]. The peak at the same wavenumber, but with significantly lower intensity had occurred in the spectrum of Sample 1, which means that the content or concentration of used chemical bonding agent is much lower. Namely, this may be a reason why the chemical bonding agent cannot be clearly visible in the SEM microphotograph, Figure 1a. Furthermore, Sample 2 did not contain a bonding agent, since no peak was noticed at the 1735 cm^{-1} (Figure 2).

It is good to mention some other peaks characteristic for viscose and polypropylene, which can be seen on the ATR-FTIR spectra. It is known that upon dissolution and subsequent regeneration of the viscose fibers, the cellulose adopts the crystal structure of cellulose II [28]. Namely, the peaks at 1364, 1156, 1035 and 895 cm^{-1} originate from the symmetric C-H bending, C-O-C asymmetric stretching from the β-glycosidic link in cellulose II, C-O stretching of cellulose II and valence vibration of the glycosidic ring, respectively [27,29,30]. Further, the wide band which occurs in the range of 3600-3000 cm^{-1} is typical for the -OH stretching intramolecular hydrogen bonds present in the crystalline cellulose II [30]. However, there are certain characteristic peaks at 2950 cm^{-1} (C-H stretch), 2840 cm^{-1} (-CH_2- symmetric vibration), and 1456 cm^{-1} (-CH_2- bending asymmetric), that assigned to the repeated units of the polypropylene [31-33]. The peak at around 1645 cm^{-1} (Figure 2) does not belong to the fibers, its presence can be attributed to the H-O-H stretching vibration of the absorbed water [29].

Volume Electrical Resistivity

The values of dc volume electrical resistivity (in further text resistivity) of the samples determined through increasing the humidity in the chamber (i.e. under moisture sorption) are shown in Figure 3.

As we expected, increased humidity in the chamber leads to higher moisture sorption, which resulted in a decreased resistivity of all investigated samples (Figure 3). The results show that for all humidity values in the chamber, and for both directions (machine direction (MD) and cross direction (CD)), the highest resistivity value shows a Sample 3, lower Sample 1, and the lowest resistivity value is recorded for

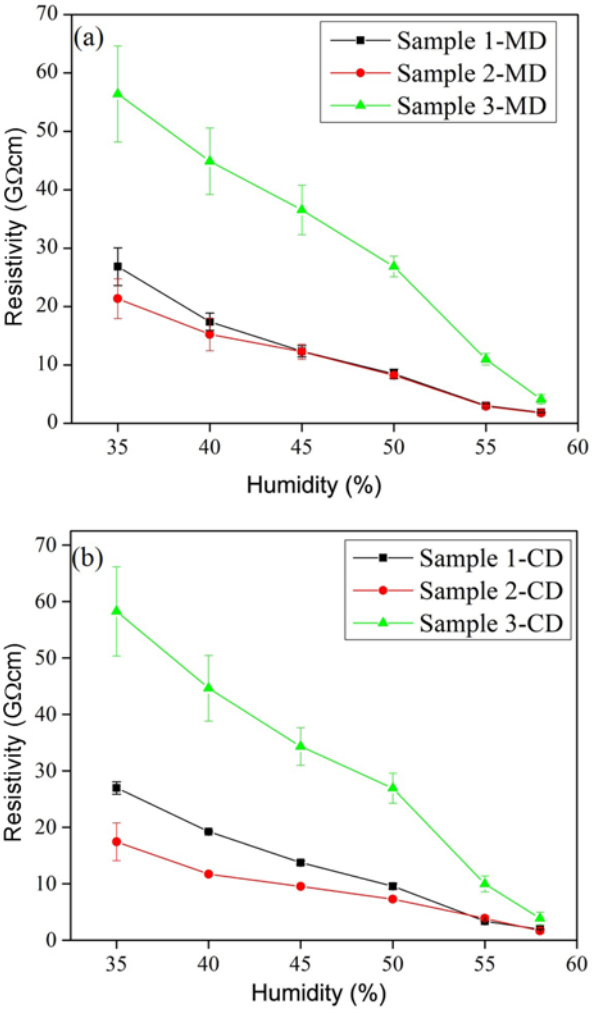

Figure 3. Resistivity of the samples measured through increasing the humidity in the chamber in the; (a) machine direction and (b) cross direction.

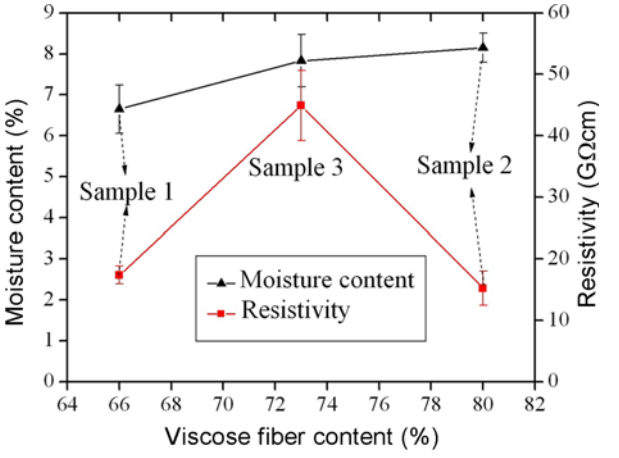

Figure 4. Influence of the viscose fiber content on the moisture content and resistivity of the nonwoven fabric in the machine direction at 40 % humidity.

Sample 2. As already mentioned, the viscose fibers have super water absorbency [1] and lower electrical resistance [9]. Thanks to the presence of a large number of hydroxyl groups, the viscose fibers are hydrophilic and enhance moisture sorption due to the interaction of their hydroxyl groups and water molecules from the air. In contrast to the viscose fibers, the polypropylene is a bad adsorbent and has high resistance values [24], since it is a non-polar hydrophobic polymer. In earlier investigations, it can be seen that the resistance of the woven samples obtained from fiber blends, is mostly dictated by the less electrical resistance component [11]. According to that, the viscose fibers with lower electrical resistance, compared to polypropylene take upon themselves transfer of greater part of a directional movement of the charge in the investigated samples [11]. Additionally, it is well known that the resistance of the textile materials decreases with increasing the moisture content [21,34]. At 40 % humidity, the viscose fibers content shows the dominant effect on the moisture sorption, as presented in Table 1 and Figure 4. Namely, Sample 2 with the highest content of viscose has the highest, while Sample 1 with the lowest viscose content has the lowest value of moisture content. Therefore, the highest moisture content in Sample 2 (8.15 %) [2], compared to something lower moisture content in Sample 3 (7.83 %) and the lowest moisture content in Sample 1 (6.65 %) [2] is the reason why Sample 2 has the lowest resistivity value. Obtained results are in accordance with the results presented in the paper [17], where the authors observed that the value of volume resistivity decreased with increasing the jute fiber content into the polypropylene/jute composite.

On the other hand, having in mind the viscose fibers content and moisture content, it is expected that Sample 3 has lower resistivity values compared to Sample 1. The much higher resistivity value of Sample 3, compared to the

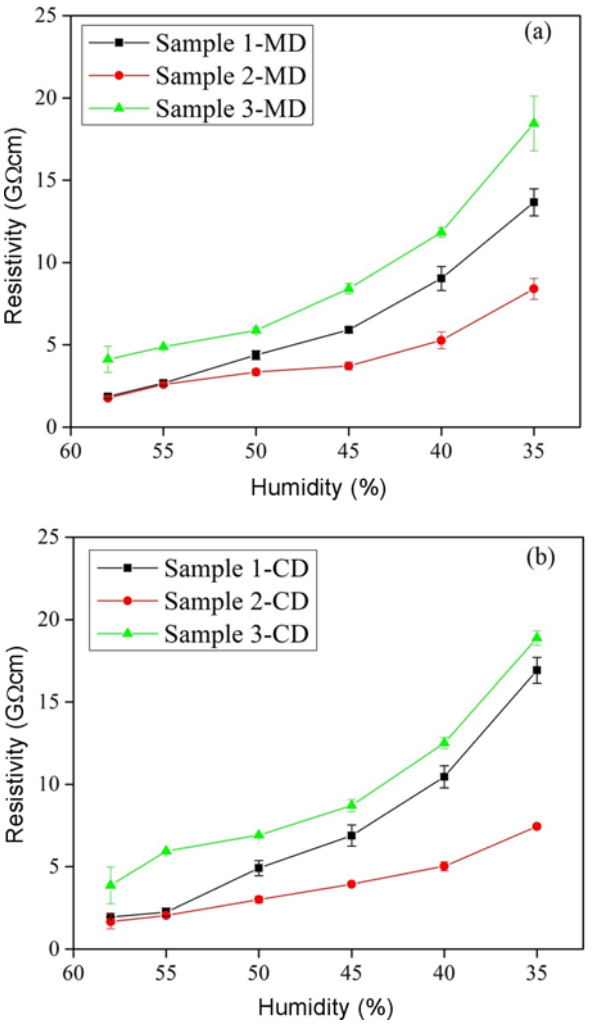

Figure 5. Resistivity of the samples measured through decreasing the humidity in the chamber in the; (a) machine direction and (b) cross direction.

other samples was the reason to investigate the presence of the chemical bonding agent, as it can be seen from the SEM microphotograph (Figure 1c). Furthermore, the intensity of the peak at 1735 cm^{-1} in the FTIR spectra (Figure 2) is in good accordance with the resistivity values. Namely, with increasing the peak intensity in the FTIR spectra due to an increase in the content or concentration of chemical bonding agent, the resistivity value increases. According to the above mentioned, we can conclude that the obtained results indicate that the highest resistivity value of Sample 3 is affected by the high resistance value of the chemical agent used for the additional bonding. The chemical bonding agent increased the resistivity of Sample 1 and Sample 3, which is particularly pronounced at low humidity (Figure 3). Even a small content of chemical agent used for bonding of Sample 1 is the reason for different resistivity values of Sample 1 and Sample 2 at low humidity (lower than 45 %). However,

at the humidity between 50 % and 58 %, there are no significant differences in the resistivity between these two samples.

The resistivity values of the samples, despite being determined through increasing, they are also determined through decreasing the humidity in the chamber (i.e. under moisture desorption) and the results are shown in Figure 5.

The decrease in the humidity, which leads to the desorption of the moisture from the samples, was accompanied by an increase in the resistivity value, as shown in Figure 5. The highest resistivity was registered for Sample 3, while the lowest for Sample 2. The samples tested in the condition of moisture desorption have the same order of resistivity as in the condition of moisture sorption (Figure 3 and Figure 5). However, compared to a condition of moisture sorption, in a condition of moisture desorption, considerably greater differences in the resistivity values between Sample 1 (with a low content or concentration of chemical bonding agent) and Sample 2 (without bonding agent) were recorded, which is particularly pronounced for humidity lower than 45 %. The decreased humidity in the chamber (from 58 % down to 35 %) leads to a gradual increase in diferences between the resistivity values of investigated samples. It is assumed that as the humidity in the chamber decreases, the moisture adsorbed on the material surfaces is firstly removed, and further decreasing of the humidity in the chamber results in the removal of the moisture absorbed by the sample volume, which is most pronounced for Sample 2. Namely, the resistivity of Sample 2, which has the highest viscose fibers content and moisture content (Table 1) is quite asymptotic approaching the x-axis (especially in the machine direction), under humidity higher than 45 %. This suggests that Sample 2 very slowly releases moisture in comparison with the relatively rapid change in the humidity in the chamber. At about 45 % humidity, a higher change in resistivity was observed, which indicates more intense moisture desorption from the material itself. This behavior could be related to the fact that water molecules that reacted with viscose fibers by forming hydrogen bonds require a longer time to be desorbed from the fibers.

From Figure 3 and Figure 5 it is noticeable that the resistivity of Sample 1 and Sample 3 is slightly higher in the cross direction compared to the machine direction. In contrast, Sample 2 has higher resistivity values in the machine direction in regard to the cross direction in both conditions (through increasing and decreasing the humidity). The resulted differences are probably due to the fiber orientation in the samples and the number of contacts established between the fibers since better contact causes an easier flow of charge [4,11]. The influence of the humidity change on the resistivity of the samples, both through increasing and decreasing the humidity in the chamber, is summarized in Table 2.

Table 2. Influence of the humidity change on the resistivity (ρ_{35}/ρ_{58}) of the investigated samples

Sample number	ρ_{35}/ρ_{58}			
	Sorption (through increasing the humidity)		Desorption (through decreasing the humidity)	
	MD	CD	MD	CD
1	14.42	13.83	7.34	8.68
2	12.06	10.44	4.76	4.46
3	13.69	15.06	4.48	4.88

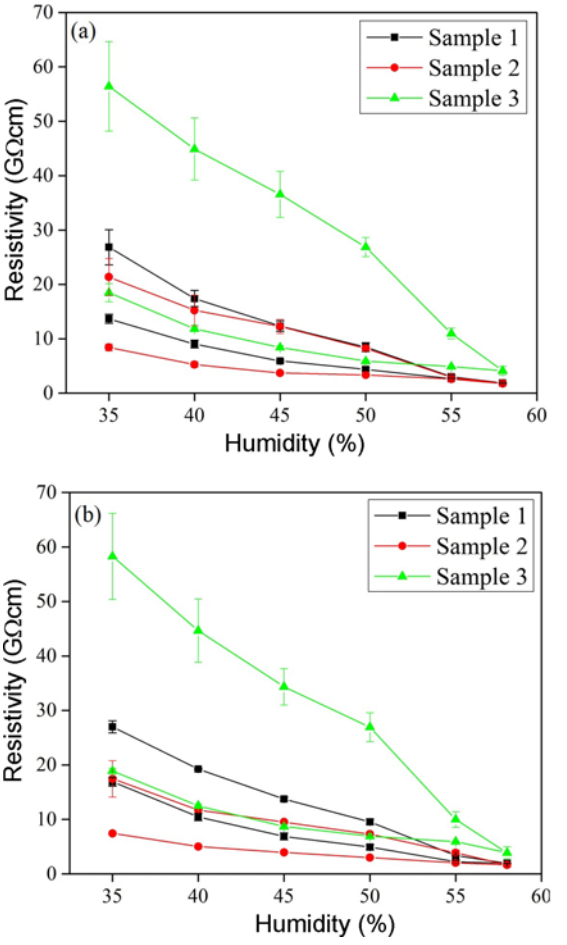

Figure 6. Hysteresis for the sample resistivity in the; (a) machine direction and (b) cross direction.

In the humidity interval from 35 % to 58 %, the smallest change in resistivity at both sorption and at desorption of moisture from the samples was recorded for Sample 2. This sample shows the highest moisture sorption at lower humidity (Table 1, Figure 4), and the highest water retention value (51.99 %) compared to Sample 1 (41.41 %) and Sample 3 (34.51 %) [2], which causes the smallest resistivity and the smallest changes in resistivity through increasing and decreasing of the humidity.

Table 3. Portion of sorbed moisture retained in the sample and removed from the sample during the desorption

Sample number	The portion of sorbed moisture retained in the sample (%)			The portion of sorbed moisture removed from the sample (%)		
	MD	CD	Arithmetic mean	MD	CD	Arithmetic mean
1	61.62	52.19	56.91	38.38	47.81	43.09
2	79.47	72.48	75.98	20.53	27.52	24.02
3	84.11	79.15	81.63	15.89	20.85	18.37

During the moisture sorption and the subsequent phase of desorption of moisture from the samples, part of the sorbed moisture retains in the material, which influences the resistivity values and leads to the appearance of hysteresis, as can be seen from Figure 6.

Figure 6 shows that the surfaces inside and under the hysteresis loops are different for all investigated samples. Since the resistivity of the textile strongly depends on the moisture content in the material, an attempt has been made to obtain information for the portion of sorbed moisture that was retained in the material after desorption, and for the portion of the sorbed moisture removed during desorption phase. From the ratio between the surface within the hysteresis loop and the surface below the sorption curve, the portion of moisture retained in the sample after the moisture desorption from the nonwoven fabrics was determined. The portion of moisture desorbed from the material was determined from the ratio of the surfaces below the desorption curve and below the sorption curve. The portion of the sorbed moisture retained in the samples, and the portion of moisture removed from the samples during the desorption phase, are shown in Table 3.

The results presented in Table 3 show that after the desorption, the smallest content of sorbed moisture was retained in Sample 1, while the highest was retained in Sample 3. The obtained results are in agreement with the fabric weight and fabric thickness of the investigated nonwoven fabrics (Table 1).

Dielectric Loss Tangent

The influence of the external (humidity and frequency) and internal factors (raw material composition and moisture content), and used chemical bonding agent on the dielectric loss tangent (tan δ) of the investigated samples will be discussed below. The frequency dependence of the dielectric loss tangent (in further text loss tangent) for investigated samples exposed for 24 hours to 40 % and 80 % humidity, and for wet samples is shown in Figure 7 (a to c).

From Figure 7a, it is evident that the loss tangent of the samples exposed 24 h to 40 % humidity gradually decreases with increase in the frequency over an investigated range (from 30 Hz to 140 kHz). The obtained results are in agreement with the literature data for polymeric fibrous structures based on natural and synthetic fibers [5,12,13,17, 19]. From the literature, it is known that the pure polypropylene is a non-polar hydrophobic material which

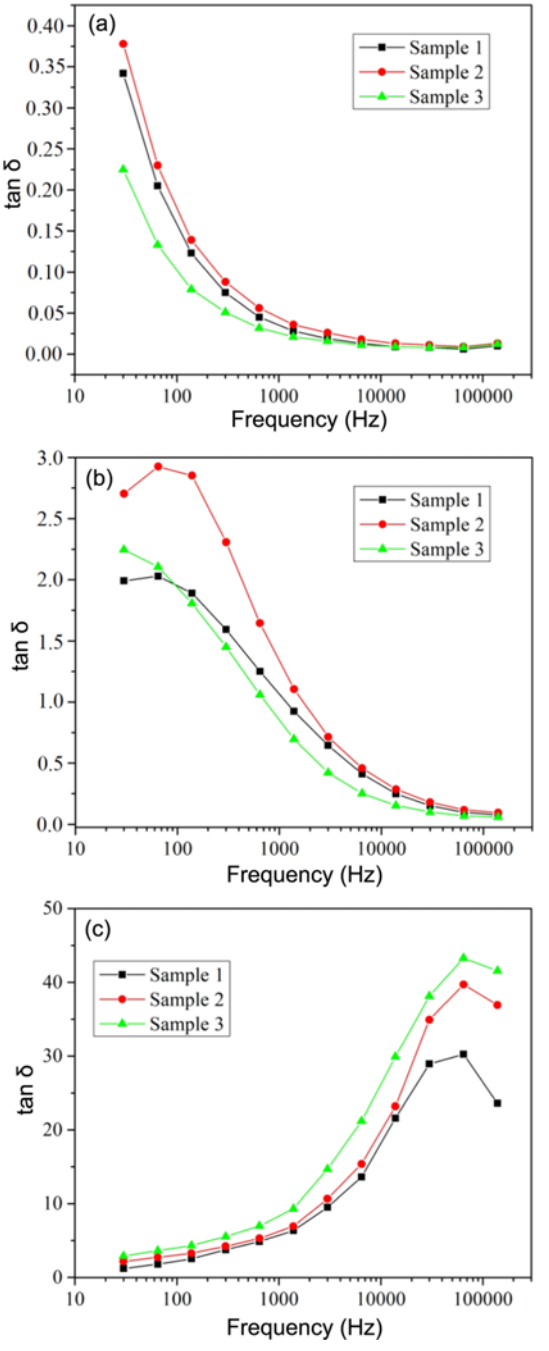

Figure 7. Frequency dependence of the loss tangent (tan δ) for; (a) samples exposed 24 h to 40 % humidity, (b) samples exposed 24 h to 80 % humidity, and (c) wet samples.

shows only instantaneous ionic and electronic polarization [20] and as a result of that, it has very low loss tangent value [17]. However, by addition of polar viscose fibers to non-polar polypropylene fibers, the orientation polarization of the blends at low frequencies increases leading to a higher loss tangent value. Especially higher loss tangent values at frequencies below 100 Hz, for all investigated samples exposed to 40 % and 80 % humidity, were obtained. At higher frequencies, the molecular vibrations are higher, therefore the complete orientation polarization of the polar groups does not take place and as a result of that, the investigated samples show a lower loss tangent value in comparison to the lower frequencies (Figure 7a and Figure 7b) [17,19]. From the results obtained for the samples exposed to 40 % and 80 % humidity above 140 Hz, it is clear that Sample 2 has the highest, while Sample 3 has the lowest loss tangent value (Figure 7a and Figure 7b). Between the three investigated samples, Sample 2 has the highest viscose fiber content (80 %) and thus the highest number of polar hydroxyl groups which participate in the polarization and leads to the highest loss tangent value. These results are in accordance with the results presented in the papers [17,19], showing that the value of the loss tangent increases with increasing content of the lignocellulosic fibers (jute or kenaf) into the composite. Based on the above mentioned, it was expected that Sample 1 has the lowest loss tangent value owing to the lowest viscose fibers content (66 %), but, it has not happened. The lowest loss tangent value of Sample 3 can be explained by the presence of the chemical bonding agent (Figure 1c and Figure 2), which restricted the movement of the dipole groups.

Comparing the Figure 7a and Figure 7b, it is evident that when the humidity increases, the loss tangent also increases. This is attributed to the increase of the moisture content in the sample and agrees with the results obtained for loss tangent for various woven fabrics at different humidity [13]. From Figure 7b (samples exposed to 80 % humidity) it can be concluded that the loss tangent value increases as the frequency increases and reaches a maximum at the frequency of 100 Hz. This relaxation can be associated with the orientational motion of the polar groups present in both fibers and water, thus Sample 2 has the highest loss tangent value which is related to the highest viscose fibers content and moisture content. For the cotton fibers, a similar effect for power factor in the frequency range from 0.1 to 1.0 kHz, at humidity from 68 to 95 %, was shown by Morton and Hearle [21]. These authors assumed that the maximum in the range from 50 Hz to100 Hz for damp cotton, occurred due to a polarization of the ion distribution in the microscopic or sub-microscopic regions in the fiber structure, or possibly even across the whole fiber. In the case of cellulosic materials, the presence of tangent loss maximum at lower frequencies, Saukkonen *et al.* [35] associated with the movement of the hydroxyl groups, water and structures formed by the introduction of water. Further increase in the frequency up to 140 kHz is followed by gradually decreases of the loss tangent for all investigated samples.

Bearing in mind the results of the moisture content determined after the exposure of the samples at 40 % and 80 % humidity (Table 1) and the results of the loss tangent determined at the same humidities (Figure 7a and Figure 7b), it can be concluded that at low humidity (40 %), loss tangent value of Sample 2 is determined by the moisture content present in the nonwoven fabric. However, for additionally chemical bonded samples (Sample 1 and Sample 3), the loss tangent values are obviously depended on the content or loss tangent value of the chemical bonding agent. As the content of the chemical bonding agent increases, the loss tangent values decreases. At higher humidity (80 %), the loss tangent value is determined by the viscose fibers and moisture content present in the sample.

A further increase of the moisture content in the samples, obtained by their immersing into the water, leads to a significant increase in their loss tangent values (Figure 7c). This behavior of the wet samples was determined by the amount of water absorbed by these samples (5.88 g for Sample 1, 9.00 g for Sample 2, and 11.82 g for Sample 3) [2], which was proportional to the samples' fabric thickness and fabric weight. In contrast to the samples tested at 40 % and 80 % humidity, the maximum of loss tangent values of the wet samples are higher and their positions are shifted toward higher frequencies. This, in general, indicates that the main change of loss tangent in the investigated viscose/ polypropylene nonwoven fabrics is a consequence of the motion of the water polar groups activated at the higher frequencies. In all three examined samples the electrode polarization relaxation peak is observed in the frequency range from 30 kHz to 140 kHz. The obtained values of loss tangent for wet samples corresponded to the literature data for the distilled water [36].

Conclusion

The presented results have shown that at all relative air humidities (35-58 %), at the sorption and desorption of moisture, and in both the machine and cross direction, the highest dc volume electrical resistivity value has Sample 3 with the higher content of chemical bonding agent. Something lower resistivity has Sample 1, with the lower content of chemical bonding agent, while the lowest resistivity has Sample 2 with the highest viscose fiber content, highest moisture content and without a chemical bonding agent. The presence of the chemical bonding agent in Sample 1 and Sample 3 and its absence in Sample 2 was confirmed using the ATR-FTIR analysis. Based on the resistivity hysteresis, it was noticed that the content of retained moisture in the material after desorption was proportional to the sample's fabric thickness and fabric weight (the highest content of

moisture retained in the Sample 3 with the highest fabric thickness and fabric weight, and the lowest in the Sample 1 with the lowest fabric thickness and fabric weight).

The results obtained for the dielectric loss tangent were in accordance with the volume electrical resistivity values. The highest value of the dielectric loss tangent in conditions of low (40 %) and high relative air humidity (80 %) was obtained for Sample 2, and the lowest for Sample 3. Furthermore, dielectric loss tangent values for the wet samples are in agreement with the samples' fabric thickness, fabric weight, and with the amount of water absorbed by these samples (the highest value of the dielectric loss tangent was obtained for Sample 3, and the lowest for Sample 1). At low humidity (40 %) the loss tangent gradually decreases with the increase in the frequency over an investigated range (from 30 Hz to 140 kHz), while at high humidity (80 %) the loss tangent maximum at a frequency of about 100 Hz for all samples was obtained. An increase in loss tangent with an increase in frequency, and the existence of the electrode polarization relaxation peak in the frequency range from 30 kHz to 140 kHz, was registered for wet samples. Their dielectric loss tangent values primarily depend on the water molecules; at a lower frequency, they grow by about an order and at a higher frequency three orders of magnitude compared to the dry samples.

It was noted that at low air humidity (40 %), the content or concentration of the used chemical bonding agent dominantly influenced the volume resistivity and dielectric loss tangent values. At higher air humidity (80 %), the loss tangent depends on the moisture and viscose fibers content in the sample, and on the content or concentration of the chemical bonding agent, while at wet condition, the loss tangent depends on the amount of water absorbed by samples. Findings of this study can help to choose the samples which ensure good electro-physical properties depending on the conditions (dry or wet) in which they will be used. Also, based on the foregoing it can be concluded that volume resistivity and dielectric loss tangent can be successfully used for monitoring the tendency of nonwoven fabrics to moisture sorption, and also volume resistivity for monitoring the tendency of nonwoven fabrics to moisture desorption.

Acknowledgments

The authors gratefully acknowledge Andrijana Zekic, Laboratory for Physics of Crystal Growth of the Faculty of Physics, University of Belgrade, for the SEM analysis, and Slavica B. Maletic, Laboratory for Condensed Matter and Physics of Materials, Faculty of Physics, University of Belgrade, for the ATR-FTIR analysis.

This work was supported by the Ministry of Education, Science and Technological Development of the Government of the Republic of Serbia [Contract No.: 451-03-68/2020-14/200135 and 451-03-68/2020-14/200162].

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