

Mathematical Model for Predicting the Resistivity of an Electroconductive Woven Structure

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Highly conductive woven fabrics (WF) can be used as electronic components. Resistivity is an intrinsic physical property of the conductive textile materials (CTM). The McLachlan model that describes the resistivity of a two-component macroscopic composite (TCMC) subjected to a constant external electric field was proposed to predict the resistivity of fabrics. The volume fraction of voids in material, the voids dimension, and a single morphology parameter were taken into account. The resistivity of a chosen WF was determined based on the model. Verification of the received results was carried out. In the case of four samples, the verification was confirmed by the high level of prediction being in the range of 83–88%. In the case of one sample, the verification was negative (26%). This allowed one to pay attention to the influence of compactness and irregularity of the woven structure on results received using the model.

Key words: Two-component composite, electroconductive woven fabric, resistivity, mathematical model

INTRODUCTION

Resistivity is one of the properties of materials that varies most widely, from 10^{-6} Ωcm for metals to 10^{18} Ωcm for electrical insulators. Material is considered electrically conductive if it has a specific resistivity of less than 10^4 Ωcm . Material is considered to have a metallic conductivity if it has a resistivity of less than 10 Ωcm .¹ Electroconductive flat textiles are developed for many applications. Especially, they are electronic components such as sensors and actuators,² electrodes for biosignal measurements,³ transmission lines,⁴ and antennas.⁵

There are many technologies that can allow one to get highly conductive textile materials (CTM).^{2,6} Conductivity of fabrics can be enabled during manufacturing. In this case, conductive fibers and yarns are used. The conductivity can also be enabled after manufacturing. In this case, conductive yarns are used during sewing, embroidering, or weaving.^{7,8} Moreover, conductive fabrics can be enabled using coating techniques such as printing,

sputtering,^{6,9–11} electroless plating, and vapor coating.

Resistivity is an intrinsic physical property of the CTM. Electroconductive properties of woven and knitted fabrics are modeled using the equivalent resistance schemes in particular.^{12–16} The fabric is seen from an electrical point of view as an electrical circuit composed of connected resistors and a battery. Yarns are ideal resistors of known resistance. The simulated structure is regular. As opposed to the presented models, the model that takes into account an actual structure of woven fabrics (WF) is proposed. It is assumed that the WF are composites that consist of two constituents: conductive and dielectric materials. Yarns are highly conductive textile materials. Yarns create a system of empty spaces and voids filled with air. Therefore, voids are dielectrics and have a size relatively small compared to the characteristic dimensions of WF. Percolation and Bruggeman's effective media theories are used to predict the electrical conductivity of components and combine most aspects of both percolation and effective media theories.¹⁷ McLachlan^{18,19} proposed an equation to describe the

resistivity of a two-component macroscopic composite (TCMC) subjected to a constant external electric field. The resistivity is a function of the composite components, the volume fraction of each, the space dimension and a single morphology parameter. The McLachlan equation¹⁹ is used to build the model for predicting resistivity of a chosen electroconductive woven structure. On the basis of this model, a designer can influence the parameters of the structure to obtain a desired resistivity of composite. However, the resistivity of a material is a parameter that can be used in multiphysics simulation software to understand the physical phenomena of the designed textile object.²⁰

MATERIALS

Electroconductive WF were chosen as research material. Raw material composition of the conductive plain-weave fabrics is as follows:

1. Nickel-plated polyester,
2. Tin + copper + silver-plated nylon,
3. Nickel + copper-plated nylon,
4. Silver-plated nylon,
5. Nickel-plated polyester.

Based on standard,²¹ sample thickness was determined. Based on standard,²² sample mass per unit area was determined. Number of warp and weft yarns was calculated using an Olympus SZX10 stereo microscope and stream motion software. Structure parameters of the WF are summarized in Table I.

Using an Olympus SZX10 stereo microscope and stream motion software, morphometric measurements of fabrics were also conducted. Images of WF were captured at total visual magnification of $9.45\times$. Parameters of the fabric structure such as d_{wa} , the width of the warp yarns, d_{we} , the width of the weft yarns, A_{wa} , the spacing of the warp yarns, and A_{we} , the spacing of the weft yarns were designated (Fig. 1).

Measurements were performed in three areas of each sample. Received parameters of the WF are summarized in Table II. Moreover, variation coefficients Vd_{wa} , Vd_{we} , VA_{wa} , and VA_{we} , for d_{wa} , d_{we} , A_{wa} , and A_{we} , respectively, are given.

The variation coefficients of the parameters are in the range from 1% to 12% (Table II). The greater the value of variation coefficient, the greater is the irregularity of woven structure. Structures of WF are shown in Fig. 2.

METHODS

In order to describe the resistivity of a TCMC type of metal-dielectric, McLachlan's equation¹⁹ was assumed. The McLachlan equation was applied to the woven structure.²³ Therefore, resistivity ρ_c of WF can be expressed as

$$\rho_c = \left(\frac{100}{C_t}\right)^{\frac{1}{1-L}} \rho_m \quad (1)$$

where ρ_m is the resistivity of the material, that is, the fabric without voids, L is the depolarization factor, and C_t is the percentage surface cover of the fabric by warp and weft yarns.

Resistivity of a rectangular or circular thin sample is given by the formula²⁴:

$$\rho_c = \sqrt{\rho_{c1}\rho_{c2}} \quad (2)$$

where ρ_{c1} and ρ_{c2} are the resistivities in directions x and y , respectively, as defined by Formula (1).

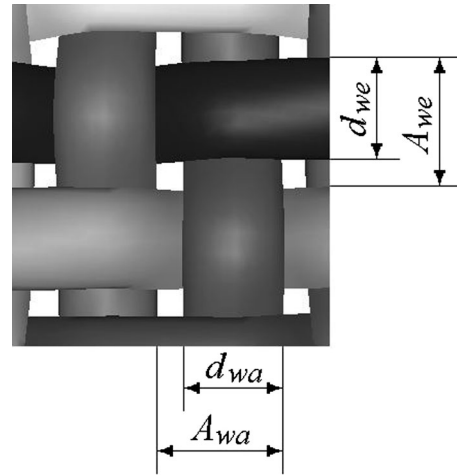


Fig. 1. Interlacing yarns in plain-weave fabric.

Table I. Structure parameters of electroconductive fabrics

Sample	Thickness (mm)	Aerial density (g/m ²)	Apparent density (kg/m ³)	Warp density (number of yarns per 1 cm)	Weft density (number of yarns per 1 cm)
1	0.078	75	962	28	20
2	0.116	77	664	34	30
3	0.176	96	545	37	29
4	0.116	72	621	38	29
5	0.188	65	346	20	13

Table II. Results of morphometric measurements of fabrics

Sample	1	2	3	4	5
d_{wa} (mm)	0.34	0.24	0.19	0.22	0.37
Vd_{wa} (%)	3	2	5	3	7
d_{we} (mm)	0.42	0.32	0.34	0.27	0.53
Vd_{we} (%)	1	2	3	2	12
A_{wa} (mm)	0.36	0.29	0.27	0.26	0.50
VA_{wa} (%)	3	5	2	2	12
A_{we} (mm)	0.49	0.33	0.34	0.35	0.79
VA_{we} (%)	3	2	4	6	11

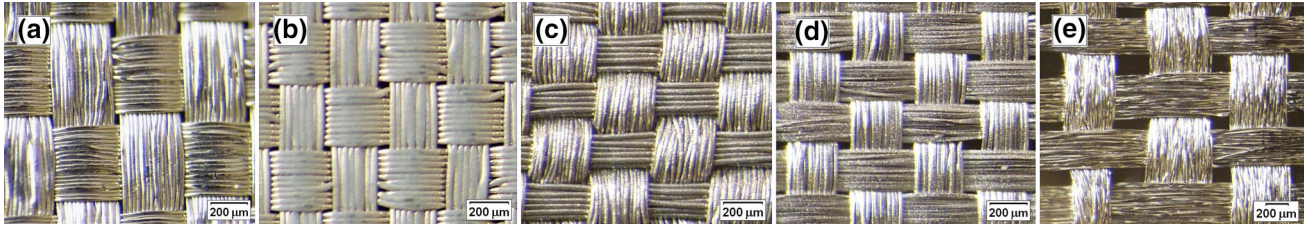


Fig. 2. Structures of WF (a) sample 1, (b) sample 2, (c) sample 3, (d) sample 4, (e) sample 5.

The percentage surface cover is expressed as²³:

$$C_t = \frac{A_{we}d_{wa} + A_{wa}d_{we} - d_{wa}d_{we}}{A_{wa}A_{we}} 100 \quad (3)$$

where d_{wa} is the width of the warp yarns, d_{we} is the width of the weft yarns, A_{wa} is the spacing of the warp yarns, and A_{we} is the spacing of the weft yarns (see Fig. 1).

The depolarization factors for directions of the three principal axes, x , y , and z , and void-shaped anisotropic ellipsoids are given by²⁵:

$$L_i = \frac{a_1 a_2 a_3}{2} \int_0^\infty \frac{ds}{(s + a_i^2) \sqrt{(s + a_1^2)(s + a_2^2)(s + a_3^2)}} \quad (4)$$

$i = 1, 2, 3$

where a_1 , a_2 , and a_3 are the semi-axes of the ellipsoid in directions x , y , and z , respectively, and $\sum_{i=1}^3 L_i = 1$.

In case of WF structure, the following dependences were adopted:

$$a_1 = 0.5(A_{wa} - d_{wa}) \quad (5)$$

$$a_2 = 0.5(A_{we} - d_{we}) \quad (6)$$

$$a_3 = 0.5 h \quad (7)$$

where h is the thickness of the fabric.

Based on Eqs. 1–4, the resistivity of the woven structure treated as TCMC is given by the formula

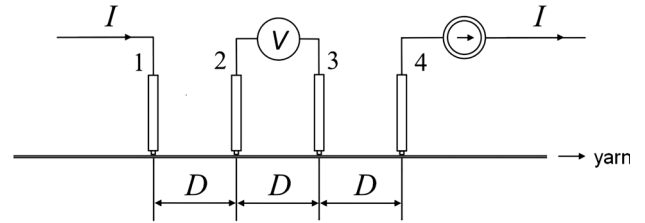


Fig. 3. Yarn resistivity measurements with four probes.

$$\rho_c = \sqrt{\rho_{wa} \rho_{we} \left(\frac{100}{C_t} \right)^{\frac{2-L_1-L_2}{(L_1-1)(L_2-1)}}} \quad (8)$$

where ρ_{wa} is the resistivity of the warp yarn and ρ_{we} is the resistivity of the weft yarn.

Resistivity ρ_{wa} and ρ_{we} of yarns can be determined using the four-probe method²⁶ and the following formula:

$$\rho_{wa} = \frac{R_{wa}}{D} s_{wa} \quad (9)$$

$$\rho_{we} = \frac{R_{we}}{D} s_{we} \quad (10)$$

where R_{wa} and R_{we} are the resistances resulting from the quotient of the measured voltage drop between the two inner probes (2 and 3) and the current I injected through the two outer probes (1 and 4) obtained for warp yarn and weft yarn, respectively (Fig. 3), D is the voltage probe spacing, and s_{wa} and s_{we} are the cross section of warp yarn and weft yarn, respectively.

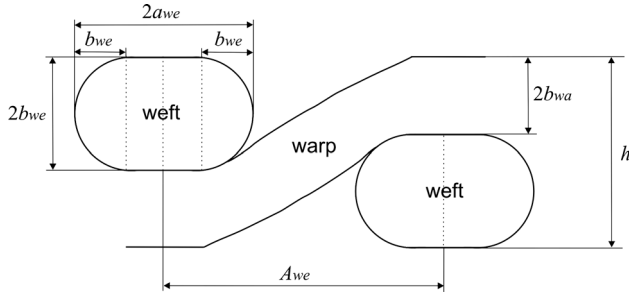


Fig. 4. Racetrack model.

The Kemp model of plain-weave fabric was assumed.^{27,28} Therefore, a racetrack geometry in a cross-section of the yarn was adopted (Fig. 4).

In Fig. 4, the cross-section of the weft yarns is presented, where b_{we} and b_{wa} are half of the shorter axis of the weft yarn and warp yarn, respectively; a_{we} and a_{wa} are half of the longer axis of the weft yarn and warp yarn, respectively; a_{wa} is invisible; A_{we} and A_{wa} are the spacing of the weft yarns and warp yarn, respectively; A_{wa} is invisible; h is the thickness of the fabric.

Based on the racetrack model, the cross-section of yarns, s_{wa} and s_{we} , can be determined. Hence, Eqs. 9 and 10 take the form:

$$\rho_{wa} = \frac{R_{wa}}{D} \left[\pi(b_{wa})^2 + 4b_{wa}(a_{wa} - b_{wa}) \right] \quad (11)$$

$$\rho_{we} = \frac{R_{we}}{D} \left[\pi(b_{we})^2 + 4b_{we}(a_{we} - b_{we}) \right] \quad (12)$$

wherein:

$$a_{wa} = 0.5d_{wa} \quad (13)$$

$$a_{we} = 0.5d_{we} \quad (14)$$

where d_{wa} and d_{we} are the width of the warp yarns and weft yarns, respectively.

To determine the resistivity ρ_{wa} and ρ_{we} according to Eqs. 11 and 12, half of the shorter axis b_{wa} and b_{we} must be calculated. For this purpose, the following simultaneous equations were solved:

$$\begin{cases} \frac{\pi(d'_{wa})^2}{4} = \pi(b_{wa})^2 + 4b_{wa}(a_{wa} - b_{wa}) \\ \frac{\pi(d'_{we})^2}{4} = \pi(b_{we})^2 + 4b_{we}(a_{we} - b_{we}) \\ h = 2b_{wa} + 2b_{we} \\ d'_{wa} = d'_{we} \end{cases} \quad (15)$$

where d'_{wa} and d'_{we} are the diameter of the warp yarn and weft yarn, respectively, before the fabric was woven.

The area of the yarn cross-section before the fabric was woven from the yarns was circular shaped. The area is the same as in the case after the fabric was woven from the yarns with a

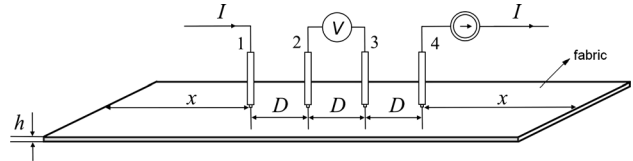


Fig. 5. Fabric resistivity measurements with four-point probes.

racetrack-shaped geometry. The diameters d'_{wa} and d'_{we} are equal because the chosen fabrics are made of the same yarns.

By solving the simultaneous Eq. 15, the diameters d'_{wa} and d'_{we} can also be calculated.

Method of Verification

The method of verification was based on comparison of the resistivity ρ_c (8) and ρ_c^* . The resistivity of WF, ρ_c^* , can be determined using a four-point probe method²⁹ and the following formula:

$$\rho_c^* = CRh \quad (16)$$

where R is the resistance resulting from the quotient of the measured voltage drop between the two inner probes (2 and 3) and the current I injected through the two outer probes (1 and 4; Fig. 5), C is the correction factor, and h is the thickness of the fabric.

Dependence (16) is valid when $h < 0.5D$, where D is the voltage probe spacing and $x > 2D$, where x is the distance from the edge of thin square sample,³⁰ shown in Fig. 5.

The resistance R (16) was calculated as an average of four resistances determined in four directions (Fig. 6). Angle φ defines the direction in which the sample resistance was measured.

The factor C can be found in Ref. 29 in the table of correction factors for the measurement of sheet resistivity with a four-point probe.

In order to assess the verification, the following indicator was proposed:

$$v = \frac{\rho_c}{\rho_c^*} 100\% \quad (17)$$

and denoted as the level of prediction in this paper. In the ideal case, $v = 100\%$.

RESULTS

Samples with an area in the shape of a 150-mm-sided square were prepared from electroconductive WF. Moreover, three warp yarns and three weft yarns of each fabric were prepared. All measurements were conducted under conditions described in standard.³¹

In order to determine the resistivity ρ_c (8), values of quantities such as C_t , L_1 , and L_2 were calculated using dependences (3)–(7). The depolarization factor in the form of a complex number was received. Only the real part was taken into account because the

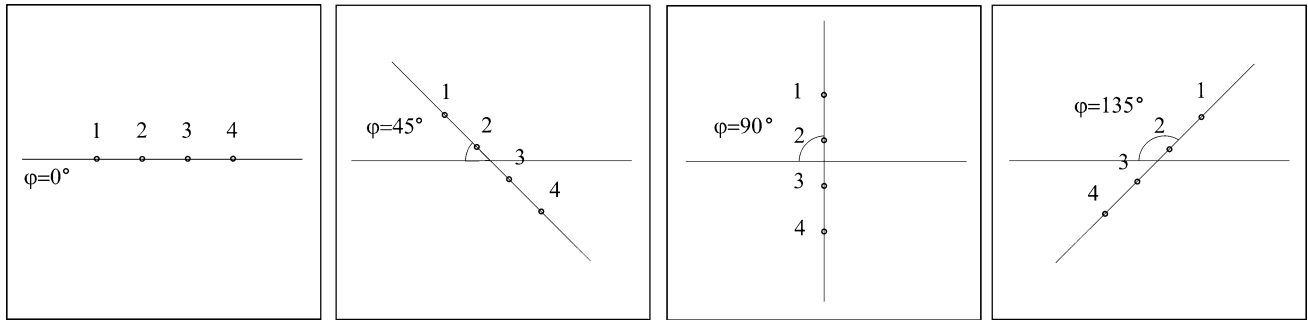


Fig. 6. Arrangement of probes in selected directions on sample surface.

Table III. Results of calculation

Sample	C_t (-)	a_1 (mm)	a_2 (mm)	a_3 (mm)	L_1 (-)	L_2 (-)
1	99.1	0.010	0.038	0.039	0.695	0.155
2	99.0	0.028	0.008	0.058	0.195	0.735
3	99.7	0.042	0.002	0.088	0.041	0.946
4	96.7	0.020	0.038	0.058	0.564	0.277
5	91.7	0.065	0.127	0.094	0.475	0.213

Table IV. Results of resistance measurements of warp and weft yarns

Sample	1		2		3		4		5	
	R_{wa} (Ω)	R_{we} (Ω)	R_{wa} (Ω)	R_{we} (Ω)	R_{wa} (Ω)	R_{we} (Ω)	R_{wa} (Ω)	R_{we} (Ω)	R_{wa} (Ω)	R_{we} (Ω)
	21.74	19.39	1.99	1.20	4.61	2.47	2.86	2.48	6.42	2.94
V (%)	6	5	5	2	4	4	2	5	2	4

Table V. Results of calculation to determine the WF resistivity

Sample	a_{wa} (mm)	a_{we} (mm)	b_{wa} (mm)	b_{we} (mm)	$d'_{wa} = d'_{we}$ (mm)	ρ_{wa} (Ωcm)	ρ_{we} (Ωcm)	ρ_c (Ωcm)
1	0.170	0.210	0.0216	0.0174	0.1350	$1.6 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$	$1.49 \cdot 10^{-3}$
2	0.120	0.160	0.0335	0.0245	0.1388	$1.5 \cdot 10^{-4}$	$9.0 \cdot 10^{-5}$	$1.18 \cdot 10^{-4}$
3	0.095	0.170	0.0585	0.0295	0.1567	$4.4 \cdot 10^{-4}$	$4.2 \cdot 10^{-4}$	$3.36 \cdot 10^{-4}$
4	0.110	0.135	0.0323	0.0257	0.1302	$1.9 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$1.92 \cdot 10^{-4}$
5	0.185	0.265	0.0562	0.0378	0.2224	$1.3 \cdot 10^{-3}$	$5.7 \cdot 10^{-4}$	$9.77 \cdot 10^{-4}$

imaginary part, being of the order of magnitude 10^{-16} or less, can be treated as numerical error and neglected. Received results are presented in Table III.

Four cylindrical silver-plated brass probes were used to measure the yarn resistance. The contact diameter of the probe was equal to 2 mm. The distance D between voltage probes was equal to 20 mm (Fig. 3). A multimeter Agilent 34410A was used as a voltmeter and its resolution was 0.1 mV. A direct current (DC) power supply Agilent E3644A was used as an ammeter and its resolution was 1 mA. Measurements of voltage drop for each yarn were repeated thrice. Received results and variation

coefficient V of resistance of warp/weft yarns are given in Table IV.

According to Eq. 15, the parameters of the race-track model were calculated. Received results, resistivity of warp yarn ρ_{wa} (11), resistivity of weft yarn ρ_{we} (12), and composite resistivity ρ_c (8) are shown in Table V.

In order to verify the received results, resistance measurements of WF were conducted. The same four cylindrical brass silver-plated probes were used. The distance x from the edge of the thin square sample was 44 mm (Fig. 5). It means that the measurement conditions specified for four-point probe method for measuring resistivity were fulfilled. A

Table VI. Results of resistance measurements of WF

Sample	1	2	3	4	5
$R(\Omega)$	0.0557	0.0031	0.0054	0.0047	0.0502
$V_{\text{dir}}(\%)$	4	1	5	1	1

Table VII. Results of verification

Sample	1	2	3	4	5
$\rho_c(\Omega\text{cm})$	$1.49 \cdot 10^{-3}$	$1.18 \cdot 10^{-4}$	$3.35 \cdot 10^{-4}$	$1.92 \cdot 10^{-4}$	$9.77 \cdot 10^{-4}$
$\rho_c^*(\Omega\text{cm})$	$1.74 \cdot 10^{-3}$	$1.42 \cdot 10^{-4}$	$3.82 \cdot 10^{-4}$	$2.20 \cdot 10^{-4}$	$3.79 \cdot 10^{-3}$
$v(\%)$	86	83	88	87	26

multimeter Agilent 34410A was used as a voltmeter and its resolution was 0.001 mV. A DC power supply Agilent E3644A was used as an ammeter and its resolution was 1 mA. Measurements of voltage drop were conducted in four directions (Fig. 6). Measurements were repeated six times. Variation coefficients of voltage in selected direction did not exceed 8%. Values of average resistance are shown in Table VI. Moreover, the variation coefficient V_{dir} of resistance in all directions is presented.

Next, according to Eq. 16, resistivity of WF, ρ_c^* , was calculated. The factor C was found in the table of correction factors.²⁹ In the case of a thin sample with an area in the shape of a 150-mm-sided square and voltage probe spacing D equals to 20 mm, the factor C is equal to 4.0095. Results are shown in Table VII.

Moreover, the level of prediction v (17) is also presented.

DISCUSSION

The flow of current in fabric takes place through both continuous elements (yarns) and the points of their contact. WF chosen for study were made of non-conductive material such as nylon or polyester. Fabrics were coated with thin adherent layers of nickel, tin, copper, or silver. In this way, high electric conductivity was obtained by the manufacturers. Therefore, we deal here with surface electrical conductivity of the fabric samples.

Electroconductive woven structure can be treated as TCMC that consists of conductive yarns and dielectric voids (empty spaces filled with air). The structure of the composite can be described using the percentage surface cover of the fabric by warp and weft yarns and parameters that describe the geometrical shape of voids. Shape and dimensions of voids in composite are measured by a depolarization factor.

Based on the indicator C_t , the percentage surface cover of the fabric by warp and weft yarns was determined. Values of C_t increase from 91.7 to 99.7 (Table III). Thus, the percentage of voids in the

fabrics is in the range of 0.3–8.3. Morphometric measurements of fabrics show the different degree of irregularity of woven structures. The variation coefficients of the received parameters are in the range from 1% to 12% (Table II).

Resistivity of warp yarn (ρ_{wa}) and weft yarn (ρ_{we}) are within the range of $1.5 \times 10^{-4} \Omega\text{cm}$ to $1.6 \times 10^{-3} \Omega\text{cm}$ and $9.0 \times 10^{-5} \Omega\text{cm}$ to $1.4 \times 10^{-3} \Omega\text{cm}$, respectively (Table V). Consequently, different resistivities of the warp and weft yarns was received though the same yarns ($d'_{\text{wa}} = d'_{\text{we}}$) that were used to make the fabric. This is due to the different surface area of the yarns that were coated with a thin layer of metal.

Taking into account the resistivity of the yarns, fabric resistivity can be predicted based on the McLachlan Eq. 8. Resistivity of fabrics, ρ_c , is in the range of $1.18 \cdot 10^{-4} \Omega\text{cm}$ to $1.49 \cdot 10^{-3} \Omega\text{cm}$ (Table VII). In the case of samples 1–4, verification is confirmed by the high level of prediction v being in the range of 83–88%.

In the case of sample 5, the conducted verification was negative; and the level of prediction is only equal to 26%. It allows one to pay attention to the following relevant factors in modeling the electroconductive properties of fabrics using the McLachlan equation. Percentage of voids in fabric is very important. A high percentage of voids affects the compactness and irregularity of the woven structure. Then, measurements of morphometric parameters of fabric structure are characterized by a large spread. One of the conditions described in standard³² is that the sample must not have any isolated holes. Using the chosen measurement method, all conditions must be fulfilled. In the case of sample 5, the percentage surface cover $C_t = 91.7\%$ and morphometric measurement spreads are in the range of 7–12%. Therefore, using the proposed model, attention should be paid to the compactness and irregularity of the WF structure.

On the other hand, by measuring the resistivity of the composite ρ_c , volume fraction of components, and voids dimensions and calculating the single

morphology parameter in the form of depolarization factor, the resistivity of material ρ_m can be estimated using the model described by Eq. 1.

CONCLUSIONS

The resistivity of electroconductive WF can be predicted based on the McLachlan equation. Using the model, a designer can influence the parameters of the structure to obtain a desired resistivity. The mathematical model based on the McLachlan equation is sensitive to compactness and irregularity of the woven structure. The proposed model is more appropriate than the resistive models that don't take into account the fabric structure but only the orientation of yarns. The resistivity of material can be also used in multiphysics simulation software to understand the physical phenomena of the designed textile object.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

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