

Electrical properties of flat textile material as inhomogeneous and anisotropic structure

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Abstract The main purpose of the study was to present the basic problems of determining surface resistance of electroconductive fabric. The attention was paid to the arrangement of electrodes on a sample. Analysis of the contact resistance between the measuring electrode and the fibrous substrate was conducted. The multi-variant research of a textile sample has shown that the electrodes arrangement is of significance for sample resistance measurement results. The arrangement of four electrodes on the edge of the sample allows the assessment of electroconductive properties of whole textile sample surface. It was found that the woven fabric sample is not homogeneous and anisotropic. Research of textile material with the coaxial electrode arrangement enable the local values of material resistance to be assessed. Results of multi-variant research have provided important knowledge about the textile material structure and its properties.

1 Introduction

Modern textiles are used for the production of sportswear of high moisture repelling and regulating properties [1, 2], in life parameter monitoring systems [3, 4], as well as in electrotherapy, e.g. as textile electrodes [5–7].

Textiles of electroconductive properties have many applications, including those in electronics [8–11]. For the determination of these properties, measurement methods are used, whereby the surface and volume sample resistances are obtained. These methods can be divided into groups.

The first group comprises resistance determination methods that use a double-electrode system described in [12]. The two electrode method is the simplest way of measuring the resistance of conducting layers. The measurement by this method is, however, burdened with a systematic error caused by the influence of the layer-measuring electrode contact resistance and the resistance of the measuring wires.

The second group is made up by the methods described in standards [13–16], where the use of three-electrode systems are recommended. The above-mentioned standards are applicable to the testing of samples exhibiting high resistance. Due to the geometry of electrodes, samples should have relatively large planar dimensions.

The third group comprises resistance determination method that use a four-electrode system. These include: the four electrode method described by Wenner [17] and the Van der Pauw method [18]. In these methods, two electrodes are power supplied from a precision current source, while the voltage drop is measured between the remaining electrodes. Thus, the effect of contact resistance is eliminated.

The fourth group encompasses methods that use more than four electrodes in resistance measurements. One of such methods is the Montgomery technique [19]. The Montgomery technique requires in total six to eight contacts arranged on the top and bottom sides of a sample. It is used for determining the resistances of anisotropic materials.

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The above-mentioned resistance determination methods can be used for flat textile product, provided that these objects fulfil specific assumptions. Textiles are special products because of their rheological features, such as elasticity, viscosity, plasticity and strength. These unique characteristics make textile materials to behave different compared with other engineering materials. The arrangement of fibres and yarns in textiles makes them, in the majority of cases, not homogeneous and anisotropic products [20–22]. They exhibit varying electrical properties depending on the testing direction. The electrical resistance of textile material depends on the raw material, from which it has been manufactured. It also depends on the geometrical dimensions of the sample and on its structure. Characteristic of woven and knitted structures is the occurrence of contact point and contact line resistances. The flow of current in flat textile products takes place both through continuous elements and through the points of their contact. Therefore, we deal here with the resistance of a single contact point, a contact line and a contact area [23, 24]. The resistance of a sample depends on the number of electrodes employed, and the size of the contact area between the electrode and the substrate. The resistance measurement is significantly influenced by the placement of the measuring electrodes on the sample [22].

Comparing results obtained using different measurement methods causes a major problem. Due to the existence of numerous factors influencing the resistance of a sample, its true value is not practically known. Therefore, the resistance of flat textile products is modelled using in particular the equivalent resistance schemes [25–27].

The main purpose of the study was to present the basic problems of determining surface resistance of electroconductive woven fabric sample. The attention was paid to the arrangement of electrodes on a sample. The measuring stand enables a multi-variant arrangement of electrodes on the fabric sample surface was built. Analysis of the contact resistance between the measuring electrode and the fibrous substrate was conducted.

2 Textile material

Resistivity is a feature of the raw material. It is known the electrical resistivity of a material is an intrinsic physical property, independent of the particular size or shape of the sample. Resistivity of flat textile material can be different.

Table 1 Parameters of the electroconductive woven fabric

Thickness (mm)	Aerial density (g/m ²)	Volumetric density (kg/m ³)	Linear density of warp/weft (dtex)	Number of warp yarns (units per 1 cm)	Number of weft yarns (units per 1 cm)
0.09	83	922	75	40	30

The electrical resistance of textile material depends on the arrangement of fibres and yarns in textiles makes them, in the majority of cases, not homogeneous and anisotropic products. It also depends on the geometrical dimensions of the sample and on its structure. Surface resistance required to determine the surface resistivity of textile material depends on measurement technique, in particular electrode arrangement on sample surface.

The research object is plain-weave polyester woven fabric as summarized in Table 1.

The fabric contains fibres with a coating such as nickel which is stable against corrosion and has a good shielding value. The woven fabric contains 15 g of pure nickel per square metre. The technology combines highly conductive and corrosive resistant nickel with woven fabric provides to good surface resistance. Moreover the manufactured electroconductive fabric is flexible and durable. The potential applications of the textile material are: filters, shielding rooms, antennas, gaskets and components to medicine applications. Microscopic image of woven fabric taken with Olympus microscope is shown in Fig. 1a. The image was captured at 7.5× magnification.

The resistance scheme was placed on the fabric repeat, in which $R_{wri,j}$ is the resistance of part of warp yarn, $R_{wfi,j}$ is the resistance of part of weft yarn, $R_{ci,j}$ is the contact resistance between warp and weft yarns (Fig. 1a). There is an electrical model of the woven fabric in Fig. 1b, where $R_{wr1,1}$, $R_{wr2,1}$ are the resistances corresponding to the selected parts of warp yarns, $R_{wf1,1}$, $R_{wf2,1}$ are the resistances corresponding to the selected parts of weft yarns, $R_{c1,1}$, $R_{c1,2}$, $R_{c2,1}$, $R_{c2,2}$ are the yarns contact resistances.

For the purpose of the study constant sample size was assumed. A sample with a measuring area in the shape of a 70 mm-side square was prepared from the electroconductive fabric. It was checked that the current–voltage characteristic for the textile sample is linear for current changing in the range from 0.010 to 1.700 A.

3 Measuring the contact resistance between the electrode and the textile substrate

The surface resistance of flat textile products is substitute resistance resulting from the yarns resistance and contact resistance occurring between the yarns forming a fibrous structure [24–26, 28]. Due to the new use of electrically conductive textiles, e.g. electrodes to muscle electrical

Fig. 1 The microscopic image: **a** the electroconductive woven fabric; **b** the electrical model of the woven fabric [24]

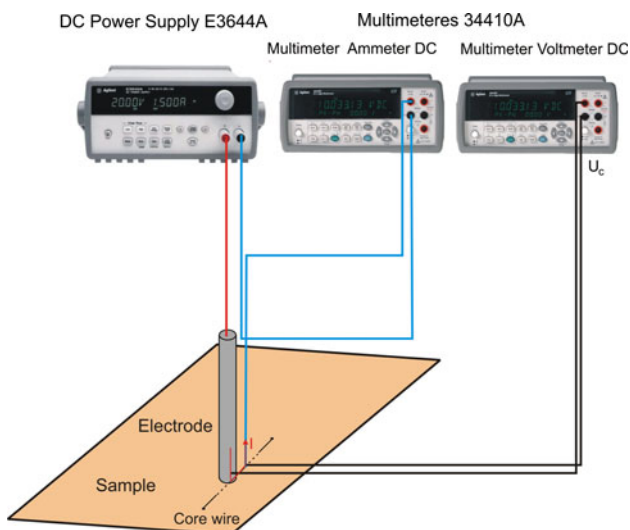
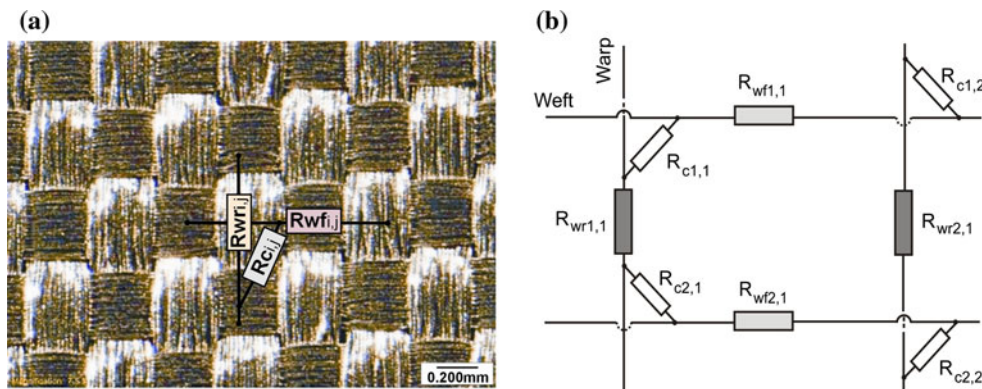


Fig. 2 Measurement system for determination of a contact resistance

stimulation [6], it is important to uniform distribution of the resistance measured between any points on the surface of the sample. The authors have proposed a new approach for measuring the resistance of the flat textile of electroconductive properties. The measurement method is based on multi-variant testing of the electroconductive properties using four cylindrical electrodes placed on the sample surface. At some scale the electrode contact area is never completely flat. There are non-conducting and conducting regions between contact area of an electrode and a sample [29–31]. This is due to the porous structure of textile materials and pressure force of the electrode. The measuring electrodes were made of brass and silver plated. The electrode contact diameter is 8 mm. The mass of a single electrode is 24 g, which means that its pressure force equals to 0.24 N. The electrodes have a comparatively small contact area with the textile substrate relative to the sample surface. The contact area of the electrode was selected so that it covers the fabric repeat. It is very important to ensure that the all yarns are contacted during measurements.

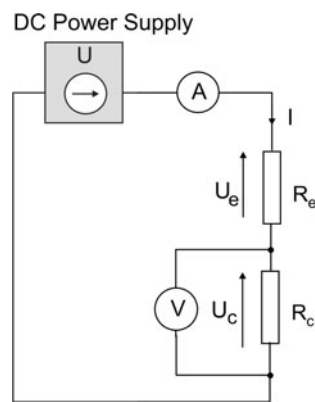


Fig. 3 Equivalent resistance scheme: I —the current; U —the voltage source; U_c —the voltage; R_e —the electrode resistance with the connecting wire; U_e —the voltage drop in the electrode; R_c —the contact resistance

In order to determine the contact resistance between the electrode and the textile sample measuring stand was built. The scheme of the stand is shown in Fig. 2.

The contact resistance measurement was conducted using the indirect method. DC Power Supply Agilent E3644A meter as voltage source was used. The current I was forced between the upper end of the electrode and a point on the thin copper measurement probe introduced into the electrically conductive sample. The probe was located in the immediate vicinity of the electrode and does not touch with the electrode. Using an Agilent 34410A ammeter the current value was recorded. Using an Agilent 34410A voltmeter voltage drop between the upper end of the electrode and a point on the wire was measured.

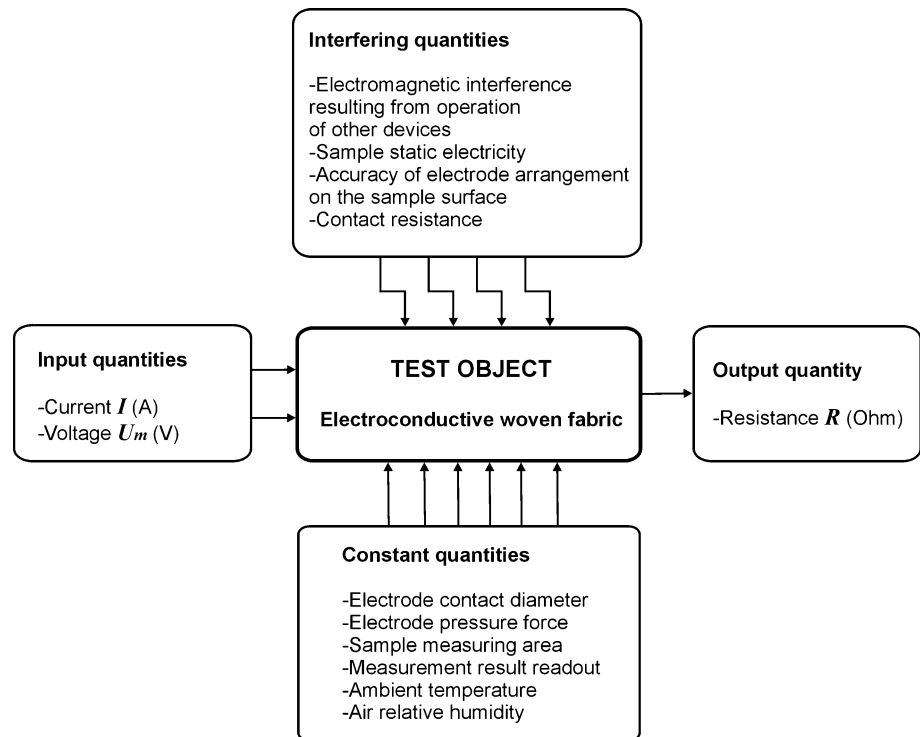
Equivalent resistance scheme of measuring system is shown in Fig. 3.

The equation resulting from the above connections (Fig. 3) is given by the following formula:

$$U - R_e I - R_c I = 0 \tag{1}$$

where: U —the voltage source; I —the current; R_e —the electrode resistance with the connecting wire; R_c —the contact resistance.

Fig. 4 The qualitative model of the research object



The contact resistance is given by the formula:

$$R_c = \frac{U_c}{I} \quad (2)$$

where: U_c —the voltage source; I —the current.

The measurements of the contact resistance were repeated five times. The average contact resistance value calculated from the formula (2) is equal to 0.049Ω . Because the value is small so it is expected that the power loss under the electrode will be small. Therefore the contact resistance has no significant impact on surface resistance of the textile sample.

4 Measurements of surface resistance of textile sample

The purpose of the study was to determine the resistance R of the textile sample and comparison of the received measurements results. The qualitative model of the research object, the woven fabric sample, is shown in Fig. 4.

The measurement model was defined as follows:

$$R = f(I, U_m) = \frac{U_m}{I} \quad (3)$$

where: I —the current flowing between one pair of electrodes; U_m —the voltage drop measured between the other pair of electrodes.

It is assumed the estimates of quantities I and U_m are uncorrelated.

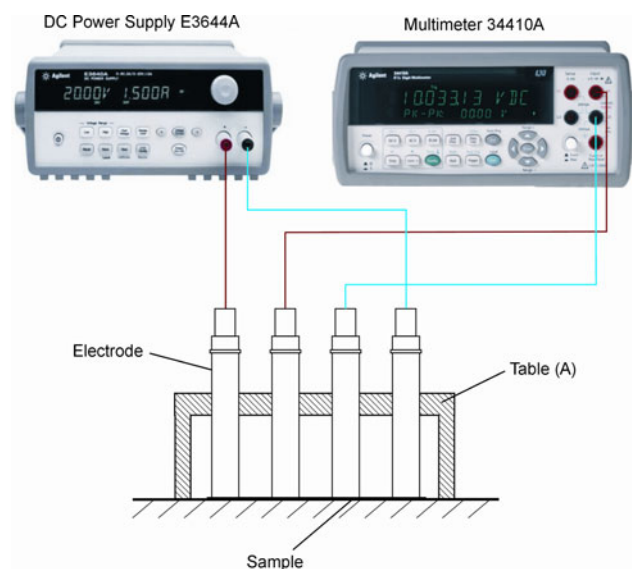


Fig. 5 The measuring stand for multi-variant textile resistance measurements

The measuring stand designed for conducting multi-variant study of the electroconductive properties of textile sample was built (Fig. 5). The measuring stand consists of the following elements:

- an Agilent 34410A multimeter;
- a DC Power Supply Agilent E3644A meter;
- a table (A) (Fig. 5) or, alternatively, table (B) (Fig. 6);
- sets consisting of four cylindrical measuring electrodes.

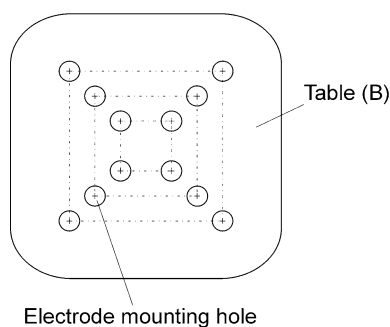


Fig. 6 Table (B) for the square-shape arrangement of electrodes on a sample—top view

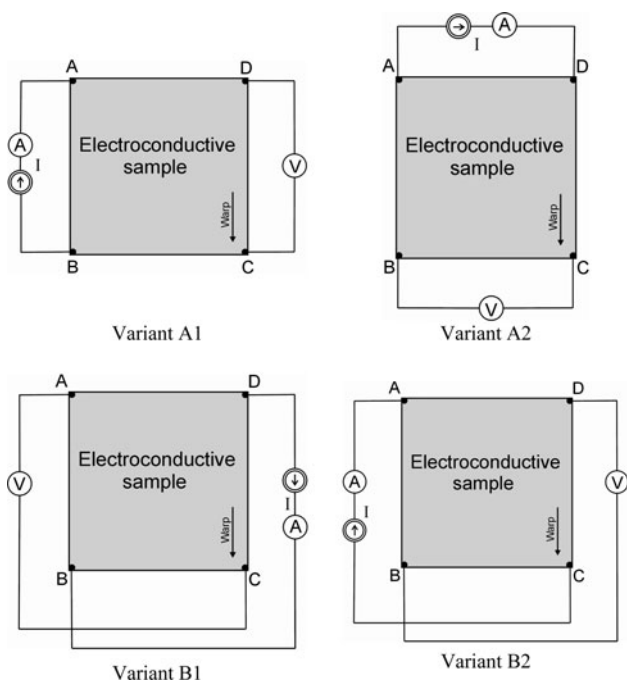


Fig. 7 Arrangement of electrodes in the four corners of the electroconductive sample (variants: A and B)

Table (A) enables the resistance measurement by the four electrode method (Fig. 5). An identical spacing between electrode mounting holes are assumed. The distance between the two outermost holes corresponds to the longest square side that can be achieved when arranging the electrodes using table (B) (Fig. 6). This table allows electrodes to be arranged in the shape of a square with a side of 70, 50 and 30 mm, respectively. The drilled holes allows the electrode to fall freely under its weight onto the fibrous substrate, while retaining the perpendicular direction of the electrode relative to the substrate.

In the case of table (A) the two outermost electrodes are connected to a current source (the DC Power Supply Agilent E3644A meter). To measure the voltage drop, the two inner electrodes are connected to the Agilent 34410A multimeter. In the case of using table (B), two adjacent

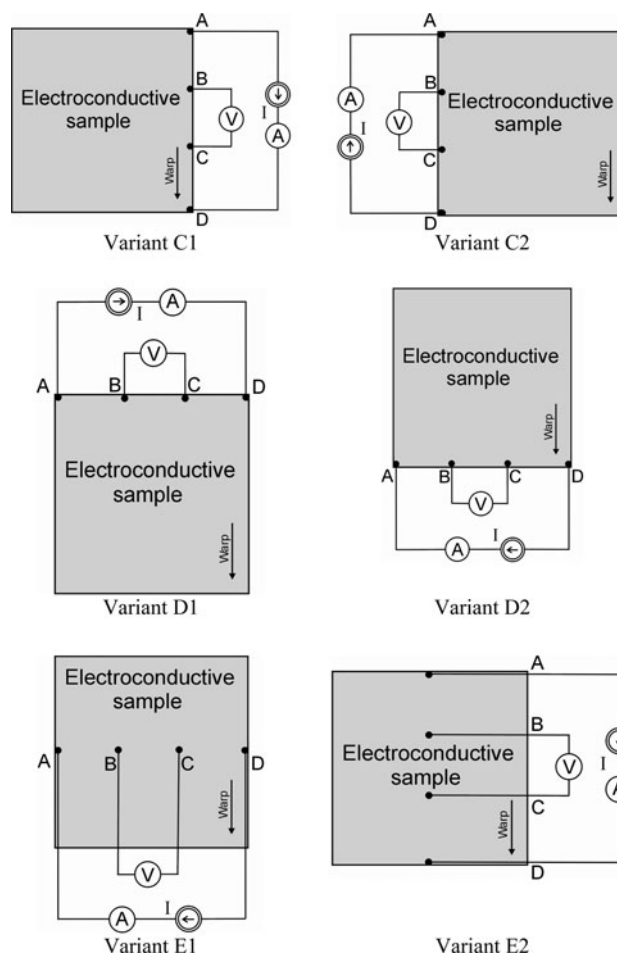


Fig. 8 Coaxial arrangement of electrodes on the surface of the electroconductive sample (variants: C, D and E)

electrodes are connected to a current source (the DC Power Supply Agilent E3644A meter). To measure the voltage drop, the two remaining electrodes are connected to the Agilent 34410A multimeter. For determining the resistance of the woven fabric sample 10 variants of electrode arrangement on the sample surface were selected which were denoted as A1, A2, B1, B2, C1, C2, D1, D2, E1, E2. The manner of electrode arrangement together with electrical circuit of the resistance measurement are shown in Figs. 7 and 8.

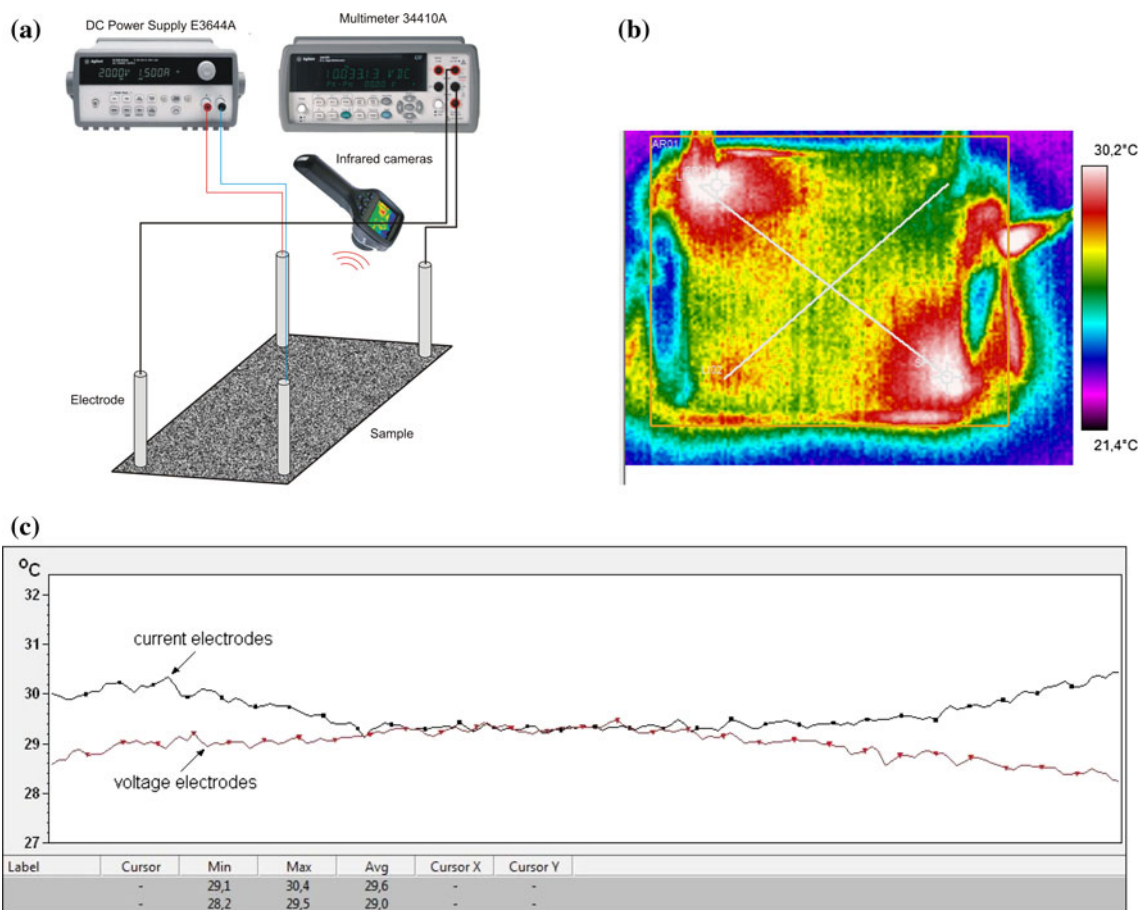
For the coaxial electrode arrangement, table (A) was used. For arranging the electrodes in the corners, on the other hand, table (B) was used.

5 Results and discussion

The measurements were conducted in according to qualitative model of the research object. The measurement

Table 2 Woven fabric resistance values

Variant	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
Resistance (Ω)	0.061	0.031	0.036	0.033	0.120	0.106	0.114	0.101	0.073	0.070
Expanded uncertainty (Ω)	0.003	0.002	0.002	0.002	0.006	0.005	0.006	0.005	0.004	0.004
Relative expanded uncertainty (%)	4.9	6.5	5.6	6.1	5.0	4.7	5.3	5.0	5.5	5.7

**Fig. 9** **a** Stand to infrared measurements, **b** infrared image of temperature distribution in sample, **c** temperature distribution among the electrodes

conducting conditions were defined with a set of constant quantities. A textile sample was subjected to acclimatization under ambient conditions, i.e. at a temperature of 21.5 °C and a relative humidity of 60 %. Then, under the same conditions, measurements were conducted. Measurement results were recorded out after 60 s from the moment of placing the electrodes on the textile sample. Each measurement was repeated three times. The average resistance values of woven fabric sample, for each electrode arrangement variant, are juxtaposed in Table 2. As a measure of measurement result uncertainty the relative expanded uncertainty was used [32]. A coverage factor of $k_p = 2$ was assumed. In calculating the B type uncertainty the rectangular distribution was assumed.

Table 2 shows that the received resistances of the sample varied in the range from 0.031 to 0.120 Ω . This means that the sample has a good electroconductive properties. The properties are connected with its fibrous structure. Sample resistance is associated with contact resistance between neighboring yarns and numerous contact points at the crossing between yarns in the sample. Received results show that the manner in which the electrodes are arranged on the surface of the textile material generally impact on its resistance. Depending on where the electrodes are located, current flows in a different way in the fibrous structure. Generally the current flows the path of easiest flow. In particular, the differences in the resistance values are shown in variants A1 ($R_{A1} = 0.061 \Omega$) and A2

($R_{A2} = 0.031 \Omega$). The results show anisotropy of electroconductive properties of the fabric. The anisotropy may result from the different number of warp and weft yarns per length unit.

It was noticed that variant B1 and B2 of electrode arrangement on the sample surface give comparable results: $R_{B1} = 0.036 \Omega$ and $R_{B2} = 0.033 \Omega$. Non zero voltage drop value shows that the sample is not homogeneous. In variant B2 of electrode arrangement on the sample surface the heat distribution patterns were observed using infrared camera (Fig. 9a).

It is visible that the current does not spread in whole sample (Fig. 9b). The current flows along the yarns. It means that there exists a significant contact resistances between interlacing yarns. Figure 9c shows temperature distribution among the current and voltage electrodes. The largest increase in temperature is $1.3 \text{ }^\circ\text{C}$ and occurs around the electrodes. This is a result of occurrence the contact resistance between electrodes and textile sample. The small increase in temperature due to the low contact resistance (0.049Ω). The temperature around the current electrodes is higher by $2.2 \text{ }^\circ\text{C}$ compared to the voltage electrodes.

Measurements conducted in according to C1, C2, D1 and D2 variants are based on the four electrode method. Four electrodes were placed on the boundaries of the conductive sample. The received resistances changed in the range from 0.101 to 0.120Ω . The resistances are greater than the resistances received in other variants. This is due to the electrodes arrangement. Generally contacts should not be too close to the boundaries of the sample that the error will not be introduced. Discussed variants give different resistance values hence the woven fabric sample is not homogenous.

The next variants (E1 and E2) assume the coaxial arrangement of the electrodes on the sample. Comparable results were obtained in the variants E1 ($R_{E1} = 0.073 \Omega$) and E2 ($R_{E2} = 0.070 \Omega$). Therefore local woven fabric resistances tested in the warp and weft direction are not significant. This may be due to the fabric structure. The fabric sample has a plain weave that is made up by yarns of the same raw-material composition and linear mass.

6 Conclusions

Results of multi-variant research can provide important knowledge about the textile material structure and its properties. The following conclusions result from the conducted analysis of woven fabric resistance measurements.

The multi-variant research of a textile sample has shown that the manner in which the electrodes are arranged on the surface of a flat textile product is of significance for sample resistance measurement results.

The arrangement of four electrodes on the edge of the sample allows the assessment of electroconductive properties of whole textile sample surface. It was found that the woven fabric sample is not homogeneous and anisotropic.

Research of textile material with the coaxial electrode arrangement on the sample surface enable the local values of material resistance to be assessed. It was found that the contacts should not be too close to the boundaries of the sample.

Measurements of the contact resistance between the textile substrate and the electrode are important part of research of electroconductive properties of textiles. Contacting is important to reduce the contact resistance between conductive sample and the measuring electrode which influences the effectively measured resistance and therefore falsifies the result on the resistance of the sample.

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Conflict of interest The authors declare that they have no conflict of interest.

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