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Measurements of the Volume and Surface Resistance of Textile Materials

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Abstract

A lot of standards describe resistance and resistivity measurement methods appropriate for a particular material or product. In the case of textile materials, some evolution has occurred in both the definitions and measurement techniques in the sphere of resistance and resistivity measurements. Some standards outline a two-electrode measurement system for surface resistance. The sole volume nature of conduction current is assumed to appear in textile materials. This assumption leads to a specific relation between the volume R_{v2} *and "surface" resistances* R_s (R_{v1})*. In this study, it was also shown that in the case of standard electrodes, the parameter* $(R_{v1}/R_{v2})\ h^2$ *(where h is the sample thickness) should be constant. The value of this parameter, determined experimentally, was found to be constant for fabrics with a volume resistivity that changed over three orders of magnitude. However, the parameter value was much lower in comparison to that predicted theoretically. The phenomenon observed was explained by the influence of additional contact resistance appearing between the sample surface and the rigid electrodes, as well as by the anisotropy of resistivity.*

Key words: *resistance measurements, volume resistance, surface resistance.*

Introduction

The definition and methods of measuring the volume and surface resistivity of electrical insulating materials have already been discussed and clearly described in [1]. In determining both resistivities, three – electrode systems are considered as the basic ones. On the one hand, the systems are capable of restricting the effect of surface currents, which influence the volume resistance (and resistivity) during the measurement of volume current. On the other hand, they are able to reduce (or eliminate) the effect of the volume component of the current, which affects the surface resistance (and resistivity) during the measurement of the surface current.

Many standards concerning the measurement of resistance and resistivity employed in textile materials recommend the usage of two-electrode systems for the measurement of surface (horizontal) resistance/resistivity [2 - 5]. It seems that in the case of textile materials with a very rich structure and highly developed surface, measurements of volume and "surface" resistances (measured in a two-electrode system) should correlate with each other. A basis for such a correlation may be the assumption that a characteristic conduction current (volume or surface), measured in a two-electrode system, flows through the bulk material. In consequence, the hypothesis (concerning only textile materials and materials with a highly developed surface and non homogenous structure, like powder) calls into question the good sense of measuring both quantities i.e. the volume and surface resistivity in a two-electrode system.

Measurements of resistance in a three-electrode system

A cross section of a sample with electrodes of circular symmetry is shown in ***Figure 1***. The circular electrode system is commonly used to measure both surface and volume resistance. A change in the character of the resistance measured is achieved by alternation in the connection system, as shown in ***Figure 2*** (see page 48).

To analyse the role of a guard electrode, it is reasonable to consider the system for measuring the volume and surface resistance separately.

In the case of measuring volume resistance, as in ***Figure 2.A***, the measuring voltage U applied between electrodes E1 and E3 enforces an electric field, especially its component normal to the surface. The current flowing from of voltage U consists of volume – I_v and surface – I_s components. If the system consists of two electrodes (lack of E2, or E2 electrode disconnected from the ground), then the current I_x, measured by ammeter A is equal to the current $I_x = I = I_v + I_s$ flowing from the source i.e. it is the sum of both components – the volume and surface. If electrode E2 is connected, as in ***Figure 2.A***, then the surface component of current I_s flows outside the ammeter, and the current measured consists, almost exclusively, of volume component I_v. Current *Is* does not flow between electrodes E1 and E2 since they are almost equipotent. The only potential difference between the electrodes is equal to the voltage drop at the inner resistance of the ammeter, which for commonly used electrometric measuring instruments does not exceed the value of 1V. Thus, ring electrode E2 plays the role of a guard electrode. The value of resistance R_{v2}, which is measured between electrodes E1 and E3, can be determined, after neglecting the boundary effects, from the dependence:

$$R_{v2} = \rho_v \frac{4h}{\pi d_1^2} \tag{1}$$

where: d_1 is the diameter of electrode E1, h the thickness of the sample of material tested, and ρ_v is the volume resistivity of the sample material.

For measuring surface resistance, the system shown in ***Figure 2.B*** is recommended. In a three-electrode system, the surface resistance R_s is measured between electrodes E1 and E2, whereas electrode E3 serves as a guard electrode. The protective action of electrode E3 consists in the reduction of the normal component of the electric field, occurring between electrodes E1 and E3, to a value close to zero, which significantly reduces or eliminates the value of the volume component of conduction current I_v. Current I_x, measured by ammeter A, is then determined mainly by the surface current I_s. The sur-

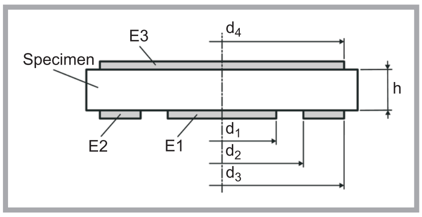

Figure 1. *Circular electrode system for the measurement of the resistance of flat samples;* $d_1 - d_4$ *– electrode diameters, h – thickness of the sample of material tested.*

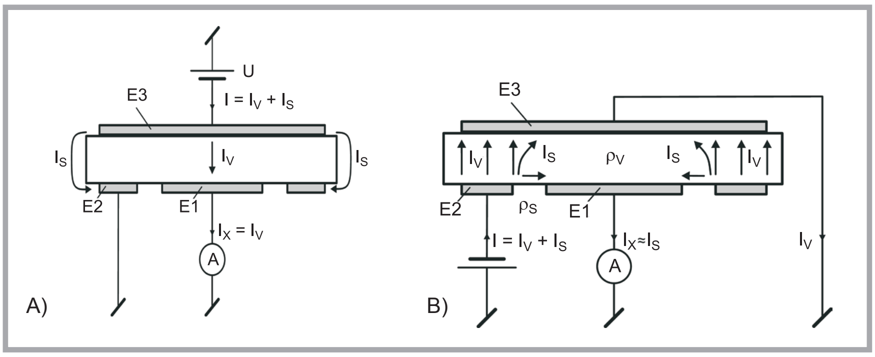

__Figure 2.__ Three-electrode system recommended for volume (A) and surface (B) resistance measurements of electrical insulating materials [1].

face current is enforced by the tangent component of the electric field occurring between electrodes E1 and E2, which are placed on the same surface of the object tested. Nevertheless, in this case the lines of the electric field would also penetrate into the bulk of the test material in the area enclosed between electrodes E1 and E2. The effect of the penetration could be removed by applying special measurement procedures [6]. An analysis of electric field distribution in the electrode system shown in ***Figure 1*** [7] indicates that the protective action of electrode E3 concerns the region beneath and in the closest neighbourhood of electrode E1. A simplified analysis of the problem under the assumption of there being no volume component of the current measured (i.e. $I_V = 0$ and $I_x = I_s$) leads to a relationship which connects the surface resistance R_s and resistivity ρ_s, in the form:

$$R_s = \frac{\rho_s}{2\pi} \ln \frac{d_2}{d_1} \tag{2}$$

where: d_1, d_2 are the radiuses of circular and ring electrodes E1 and E2, respectively, and R_s is the value of surface resistance measured (usually determined from the measurement of current I_x).

Measurement of surface resistance in a system with an insulated guard electrode

If a sample of the test material is located on a dielectric spacer with the resistance significantly exceeding the expected value of the volume resistance of the fabric [2 - 5], then it is not possible to control the potential on its bottom surface nor the distribution of the electric field inside the sample. The surface potential of the bottom surface of the sample located under electrode E2 starts to rise (with the Maxwell time constant), and the lines of the electric field penetrate the fabric volume, which results in an increase in the volume component I_V of current I_x, measured by ammeter A, ***Figure 3.B***. The three-electrode system transforms into a two electrode one. In consequence, the distribution of the electric field in the volume of the sample becomes more and more similar to the distribution existing in the system of concentric cylindrical electrodes, where the electric field penetrates through the whole thickness of the coating tested – ***Figure 3.C***. In spite of significant changes in both the electric field distribution and current flow, the standards mentioned recommend, also in this case, the application of dependence (2) to determine the (horizontal) surface resistivity ρ_S.

It should be pointed out that in the two electrode system, we can measure a certain value of resistance R_x existing between the electrodes, whose character (surface or volume) can only be anticipated with a preliminary assumption of the character of the current measured. We cannot predict in advance whether the current flows through the volume or the surface of the sample tested and are not able to control the path of its flow.

If we put forward the hypothesis that in the fabric the conduction current I_x flows exclusively in its volume, then the resistance R_x can be determined from the dependence of the volume resistance of a plane-parallel sample equipped with a concentric system of cylindrical electrodes, as shown in ***Figure 3.C***.

In the case of ignoring (lack) the surface component of the current I_x measured – according to the hypothesis that there is only a volume component of the current – the value of resistance R_{v1} between the inner cylindrical electrode E1 and the outer ring electrode E2 can be determined from the dependence:

$$R_{v1} = \frac{\rho_v}{2\pi h} \ln \frac{d_2}{d_1} \tag{3}$$

where: d_1, d_2 are the radiuses of electrodes E1 and E2, R_{v1} the value of volume resistance estimated from the measurement of current I_x flowing between electrodes E1 and E2, and h is the sample thickness. It should be noted that in this case the resistance R_x measured is the volume resistance R_{v1} of the sample of test material (when current I_x flows in a tangential direction relative to the sample surface).

Comparison of bulk resistances in different electrode systems

Assuming that the 'surface' resistance measured in a two electrode system (with an insulating spacer) is in fact the volume resistance in a different electrode arrangement, one could expect some correlation between the 'surface' thus defined and volume resistances measured in a particular electrode system. In the case of the electrode system considered above, after dividing equation (3) by (1), we get:

$$\frac{R_{v1}}{R_{v2}} = \frac{d_1^2}{8h^2} \ln \frac{d_2}{d_1} \tag{4}$$

For standard electrodes, recommended by the above standards, i.e. $d_1 = 50.4$ mm and $d_2 = 69.2$ mm, we obtain:

$$\frac{R_{v1}}{R_{v2}} = 0.0396 \frac{d_1^2}{h^2} \tag{5}$$

or:

$$\frac{R_{v1}}{R_{v2}} h^2 = 1.01 \times 10^{-4}\ \text{m}^2 = const. \tag{6}$$

where: h is thickness of the sample in m.

Dependence (6) highlights that the quotient of the 'surface" resistance (here denoted as R_{v1}) and volume resistance R_{v2} multiplied by h^2 should be constant for a particular electrode system.

Measuring system

Measurements of resistance were carried out with the use of rigid electrodes according to the procedure recommended by the standard [5]. For the resistance measurements a Kithley 6517A instrument was applied. The measurements of resistances R_{v1} and R_{v2} were performed in the arrangements shown in ***Figures 3.B*** and ***2.A***, respectively. As shown in ***Figure 3B***, an insulating spacer, recommended by the standards, was placed between the sample surface and electrode E3 (measurement of R_{v1}). The measurements were carried out in air, in the following conditions: temperature T = 23 °C, relative humidity of air h = 40%, measuring voltage U = 10.0 V and U = 100.0 V. The measurements were conducted under the pressure of the electrodes, without an elastic spacer placed on electrode E3.

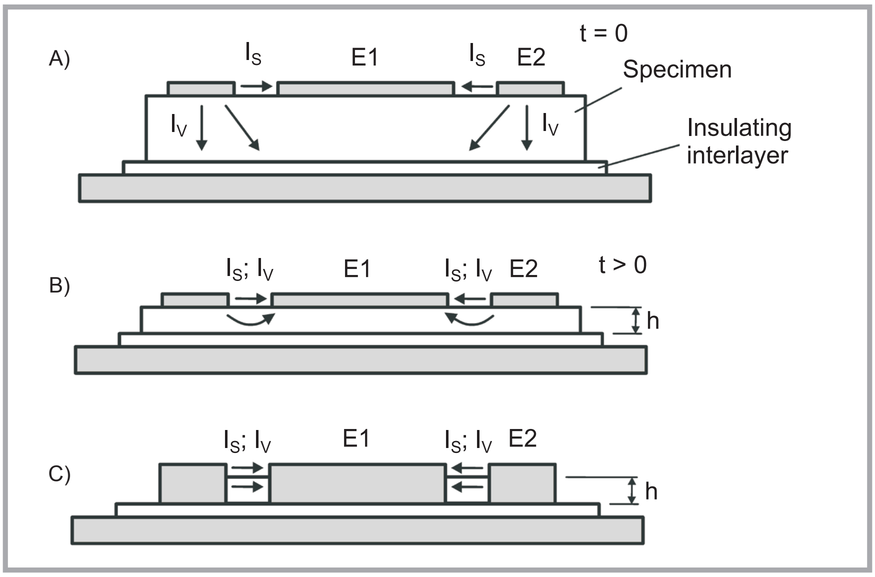

Figure 3. *Evolution of a three electrode system for the measurement of the (horizontal) surface resistance in a system with an insulated guard electrode. (A) the state just after switching on the voltage, (B) a steady state, (C) an equivalent system of electrodes.*

Table 1. *Results of measurements of resistances R_{v2} and R_{v1} of selected fabrics obtained in a standard electrode arrangement at the measuring voltage U = 10 V; R_{v2} (3E) – volume resistance measured between electrodes E1 and E3 in a three electrode system; R_{v1} (2E) – 'surface' and 'horizontal' resistance measured according to the standards between electrodes E1 and E2 in a two electrode system with a rigid insulating spacer placed on electrode E3. PA – polyamide fabrics (G) – thick, (C) – thin; PP-PA – polypropylene/polyamide fabric.*

Fabric	R_{v2} (3E)×10^{-12}, Ω	R_{v1} (2E)×10^{-12}, Ω	h, mm	ρ_v (3E)×10^{-12}, Ωm	$(R_{v1}/R_{v2})h^2\times10^7$, m^2
Cotton	0.0075 – 0.0077	0.0090 – 0.0095	0.48	0.031 – 0.036	2.7-2.9
PA-G	11 – 15	1.5 – 2.7	0.60	36 – 39	3.6-8.1×10^{-7}
PP-PA	2.0 – 3.0	1.7 – 1.8	0.66	6.1 – 9.1	2.5-4.0×10^{-7}
PA-C	6.0 – 7.0	1.5 – 2.5	0.10	0.012 – 0.014	2.1-4.2×10^{-7}

Results of measurements

The measurements of resistances R_{v2} and R_{v1} were carried out for several kinds of fabrics. The material of the fibres and the results obtained with standard electrodes are collected in ***Table 1***.

Conclusions

The results of measurements presented lead to the following conclusions:

- the value of parameter $(R_{v1}/R_{v2})h^2$ determined from experimental data of fabrics with a volume resistance ranging within three orders of magnitude varies in the range of $2.1 - 8.1\times10^{-7}$ m^{-2}, which confirms the previous hypothesis, assuming that in the measurements of 'surface' resistance in a two electrode system, the conduction current flows in the volume of the sample;
- the value of parameter $(R_{v1}/R_{v2})h^2$ determined from experimental data is lower than that given by dependence (6). The discrepancy may follow from the occurrence of some additional resistance at the interface of the electrode-fabric. It may be assumed that the contact resistance, connected with the volume resistance of the sample in series, depends on the surface of the electrode, its pressure, as well as on the mechanical properties of the fibres and other factors. For the standard electrode system employed and average thickness of fabrics, relation $R_{v1} >> R_{v2}$ should be valid. In conditions where electrodes E1 and E3 have a similar surface area, values of contact resistance exceeding resistances R_{v1} and R_{v2} could be expected. Therefore, the influence of the contact resistance on the result of the measurement of volume resistance R_{v2} is higher than that on R_{v1}, which, in consequence, leads to a reduction in the actual value of parameter $(R_{v1}/R_{v2})h^2$;
- another factor influencing the reduction in parameter $(R_{v1}/R_{v2})h^2$ may be the strong anisotropy of volume resistivity ρ_v, which may be expected in the fabrics. Dependence (6) was determined considering the isotropic character of the volume resistivity. Minor differences in the values of parameter $(R_{v1}/R_{v2})h^2$ obtained for different fabrics may suggest that the anisotropy of the volume resistivity (measured as a ratio of volume resistances in normal and tangential directions relative to the fabric surface) is similar for all the fabrics.

Acknowledgment

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