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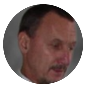

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DEVELOPMENT OF A HYBRID ELECTROMAGNETIC SHIELDING FABRIC

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1 Introduction

According to World Health Organization [1], exposure to electromagnetic fields is not a new phenomenon. However, during the 20th century, environmental exposure to man-made electromagnetic fields has been steadily increasing as growing electricity demand, ever-advancing technologies and changes in social behavior.

Everyone is exposed to a complex mix of weak electric and magnetic fields, both at home and at work. Sources of such emissions could include generation and transmission of electricity, domestic appliances and industrial equipment, telecommunications and broadcasting. If the electromagnetic waves are not isolated effectively, they will cause interference with each other and result in technical errors. If somebody gets exposed under the electromagnetic, radiate environment, physical harms may occur on human body [2,3].

Metal is considered to be the best electromagnetic shielding material due its conductivity and permeability, but it is expensive, heavy, and may also have thermal expansion and metal oxidation, or corrosion problems associated with its use. In contrast, most synthetic fabrics are electrically insulating and transparent to electromagnetic radiation [4].

In recent years, conductive fabrics have obtained increased attention for electromagnetic shielding and anti-electrostatic purposes. This is mainly due to their desirable flexibility and lightweight. One way how conductive fabrics can be created is by using minute electrically conductive fibers. They can be produced in filament or staple lengths and can be incorporate with traditional non-conductive fibers to create yarns that possess varying degrees of conductivity. Another way represents conductive coatings which can transform substrates into electrically conductive materials without significantly altering the existing substrate properties. They can be applied to the surface of fibers, yarns or fabrics. The most common are metal and conductive polymer coatings.

In this paper, a hybrid electromagnetic shielding fabrics are introduced. An effect of metal content is studied and a form of relation between resistivity and total shielding effectiveness S_T is proposed. First group of fabrics is made of hybrid yarns containing metal staple fibers, second group of fabric are polypropylene twill with mesh composed of hybrid yarns containing POP and metal fiber.

2 Theory on Shielding of Electromagnetic Interference

An electromagnetic field is built up from various electric E and magnetic field H components. An electric field is created by a voltage difference and magnetic field is created by a moving charge, i.e. by a current. Every current is thus accompanied by both an electric and a magnetic field. Electromagnetic radiation consists of waves, see Fig. 1.

EMI shielding consists of two regions, the near field shielding region and far field shielding region. The amount of attenuation due to shield depends on the electromagnetic waves reflection from the shield surface, absorption of the waves into the shield and the multiple reflections of the waves at various surfaces or interfaces in the shield. The multiple reflections require the presence of large surface area (porous or foam) or interface area (composite material containing fillers with large surface area) in the shields. The loss connected with multiple reflections can be neglected when the distance between the reflecting surfaces or interfaces is large compared to the skin depth δ [m] (the penetration depth) defined as:

$$\sigma = \frac{1}{\sqrt{\pi\, f\, \mu K}}, \qquad (1)$$

where f [Hz] is the frequency, μ is the magnetic permeability equal to $\mu_0.\mu_r$, μ_0 is the absolute permeability of free space (air = 4π 10^{-7}) and K [S m^{-1}] is the electrical conductivity. An electric field at a high frequency penetrates only the near surface region of a conductor. The amplitude of the wave decreases exponentially as the wave penetrates the conductor. The depth at which the amplitude is decreased to 1/e of the value at the surface is called the "skin depth," and the phenomenon is known as the "skin effect" [5].

Efficiency of electromagnetic shields is commonly expressed by the total shielding effectiveness S_T [dB], which represents the ratio between power P_2 [W] received with the shield is present and power P_1 received without the shield is present:

$$S_T = -10 \log\left(\frac{P_2}{P_1}\right), \qquad (2)$$

where log(x) is decimal logarithm.

The electromagnetic shielding efficiency of element is characterized by its electric conductivity, permittivity, and permeability, parameters of source and properties of ambient surrounding. Basic proposed numerical models of fabric S_T are based either on electrical properties (especially volume conductivity) of element [5,6,7,9,10] or on analysis of leakage through of opening in textile [8].

3 Experimental part

3.1 Hybrid yarns

Hybrid yarns were composed of polypropylene and different content of staple stainless steel metal fiber (1, 3, 5, 10, 15, 20 %). The aspect ratio (length/diameter ratio, l/d) of the SS is 6250 used in this study, since the diameter of the SS is 8 μm and the fiber length of the SS is 50 mm. See Fig. 2 for microscopic image of hybrid yarn.

3.2 Hybrid fabrics

The twelve fabrics with the same structure (weft and warp fineness 51 tex, warp sett 20 1/cm, weft sett 19 1/cm and twill weave) were used. The first six samples were made of 100% hybrid yarn containing different portion of conductive phase, second six samples are polypropylene twill with mesh (5x5 mm) composed of the hybrid yarn, see Fig. 3. Thickness of samples was 0,83 mm. Details about fabrics are given in the Table 1.

3.3 Characterization

3.3.1 Electric resistivity

Volume resistivity was measured according to the standard ČSN 34 1382, at the temperature T = 22,3°C and relative humidity RH = 40,7 %. Volume resistivity is measured by applying a voltage potential across opposite sides of the sample and measuring the resultant current through sample. Volume resistivity ρ_V [Ω.cm] was calculated from relation:

$$\rho_V = R_V \frac{S}{h}, \qquad (3)$$

where R_V [Ω] is volume resistance reading, h is thickness of fabric [cm], S is surface area of electrodes [cm^2]. The mean values of ρ_V are listed in Table 2.

3.3.2 Electromagnetic shielding efficiency

Electromagnetic shielding was characterized by the attenuation of electromagnetic field power density by using of simple device (see Fig. 4).

Basic parts of device are two waveguides. One waveguide is connected with receiving wire (antenna). Textile sample is placed on the entrance of second waveguide. The end of this waveguide is filled by foam saturated by carbon absorbing the electromagnetic field passed through sample. Sample is oriented perpendicularly the electromagnetic waves. Transmitting antenna is placed in front of first waveguide input. As source of electromagnetic field the

ZigBee module working at frequency 2.4 GHz is used. The total shielding effectiveness S_T [dB], is calculated from Eq. (2) where P_1 [W m^{-2}] is input power density and power P_2 is power density after passing through sample. The mean values of S_T are given in the last column of Table 2. It was found that the S_T in the direction of weft and warp were the same.

3.3.3 Chosen comfort properties

The bending rigidity, crease durability, drapability, abrasion resistance and heat conductivity were studied by the help of conventional measuring techniques. Samples with the lowest and the highest content of conductive phase were compared.

3.4 Results and discussion

3.4.1 Electrical properties

The dependence of volume resistivity ρ_V of sample on percentage of conductive component P [%] (metal fiber) in hybrid yarn for samples 1 – 6 is given in the Fig. 5a-c. It is well known, that the volume electrical resistivity ρ_V dependence on the amount of conductive component P is different for the range below and above of so called percolation threshold V_o. The ρ_V is strongly decreasing function of P below V_o. The ρ_V is more slowly decreasing function of P in the range above V_o for samples 1 – 6.

The dependence of volume resistivity ρ_V of sample on percentage of conductive component P [%] (metal fiber) in hybrid yarn creating conductive mesh of 7 – 12 samples is given in the Fig. 6.

The dependence of ρ_V on P for the range below V_o was simply approximated by line for samples 1A – 6A (see. Fig. 5c). In the range above V_o can be dependence of R_V on P expressed by simple power function (adopted from [5])

$$\rho_V = \rho_C \cdot P^E , \qquad (4)$$

where ρ_C is volume resistivity for $P = 1\%$ of conductive component in hybrid yarn and parameter E is dependent on the structure of conductive component.

3.4.2 Electromagnetic shielding efficiency

The dependence of total shielding effectiveness S_T on the percentage of conductive component P is shown in Fig 7 a,b.

The very good linearity is clearly visible. The solid line in this graph corresponds to the linear model with parameters obtained by the minimizing sum of squared differences. This linear model can be used for prediction of the value of P for sufficient shielding. For example for samples 1 – 6:

$$P = \frac{S_T - 27{,}06}{0{,}4458} , \qquad (5)$$

For example the $ST = 40$ can be obtained at conductive component concentration $P = 29.02\ \%$. The prediction ability of this line model is restricted to the content of conductive component above percolation threshold V_o.

3.4.3 Corelation between electric resistance and electromagnetic shielding

In sequel the samples with content of conductive component higher than P = 3 % are analyzed because belongs to the same region. The dependence of total shielding effectiveness ST on logarithms of volume resistivity $log(R_V)$ is shown in Fig. 8 a,b.

The approximate linearity is visible. The solid lines in this graph correspond to the linear model with parameters obtained by the minimizing sum of squared differences. Corresponding correlation coefficient r = 0.98, resp. ? indicates the good quality of fit. This graph clearly indicates that for sufficiently high frequencies it is sufficient to measure only the electric field characteristics.

3.4.4 Chosen comfort properties

Bending rigidity and crease durability was decreased by increasing of conductive phase in sample. Therefore, drapability was enhanced. Abrasion resistance became worse with increasing content of metal fiber in sample. Heat conductivity of samples did not statistically changed by increasing of metal fiber content.

3.4.5 Comparison

Table 3 presents the comparison of chosen types of conductive fabric with developed hybrid weaves. Although some of the chosen materials have higher S_T than developed hybrid waves, not all of them are suitable for using like an ordinary fabric (e.g. flexibility, drapability, durability, comfort properties, sewing, washing etc.)

4 Conclusion

Low cost conductive fabrics with sufficient electromagnetic shielding efficiency conserving the main properties, e.g. drapability and process ability characteristics were created.

Weft fabrics with the same structure, different portion of conductive phase in hybrid yarn and different placement of the hybrid yarn were studied. Hybrid yarns forming weaves were composed of polypropylene and staple stainless steel fiber. Samples were characterized by its volume resistivity (standardized method) and its electromagnetic shielding efficiency was measured by means of simple waveguide type device on frequency 2.4 GHz.

So called percolation threshold, dependence of resistivity and total shielding effectiveness S_T on the amount of conductive component P in hybrid yarn and dependence of total shielding effectiveness S_T on volume resistivity was examined. It is clear, that the portion of conductive component has a significant effect on increasing conductivity (decreasing resistivity) and improvement of electromagnetic shielding efficiency. Dependence between volume resistivity and percentage of conductive phase in hybrid yarn above percolation threshold is possible to express by simple power function adopted from literature. The dependence between total shielding effectiveness and percentage of conductive phase in hybrid yarn above percolation threshold V_0 is possible to express by linear function. Model for prediction of the value P for desired shielding was proposed. It was shown that dependence of total shielding effectiveness S_T on volume resistivity of fabric above percolation threshold V_0 is nearly linear at the frequency of 2.4 GHz.

ACKNOWLEDGMENT

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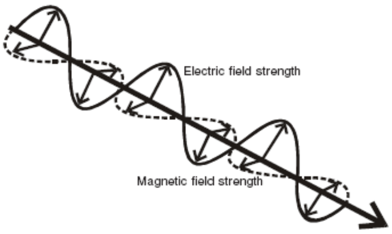


Fig. 1. Electromagnetic waves

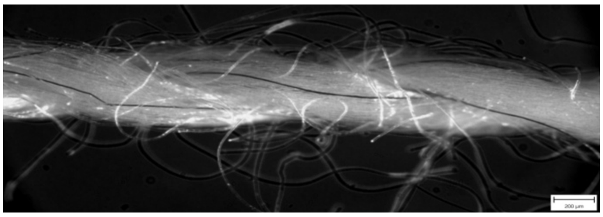
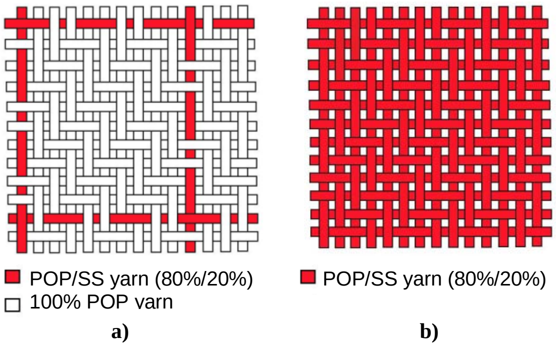


Fig. 2. Microscopic images of chosen hybrid yarn containing 5% of stainless steel fibre (diameter of fibre is around 9μm).



a) b)

Fig. 3. Scheme of chosen studied samples: a) sample with mesh composed of the most conductive yarn (20% of conductive phase), b) sample made of 100% hybrid yarn (20% of conductive phase).

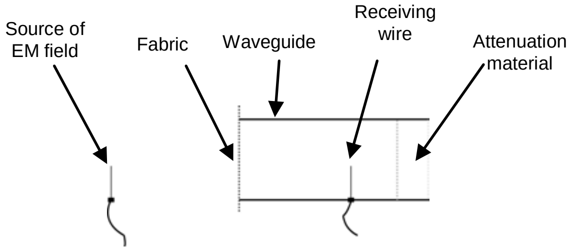


Fig. 4. Scheme of device for measurement of elekctromagnetic shielding efficiency.

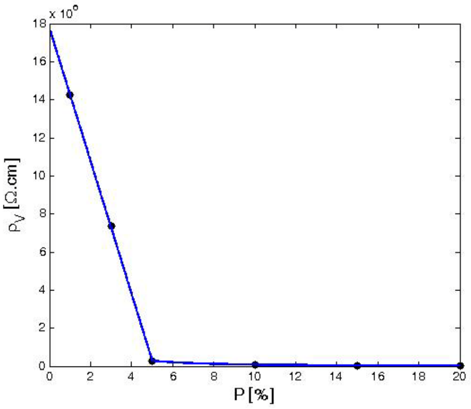


Fig. 5a. The dependence between volume resistivity and percentage of conductive phase in sample – total view.

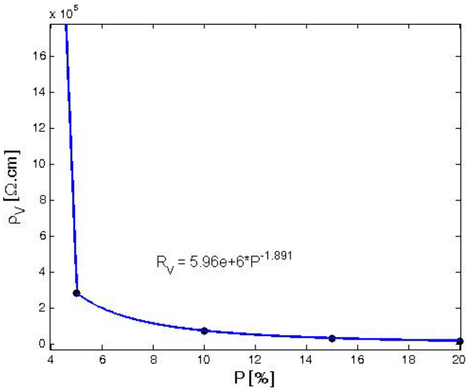


Fig. 5b. The dependence between volume resistivity and percentage of conductive phase in sample – above percolation threshold.

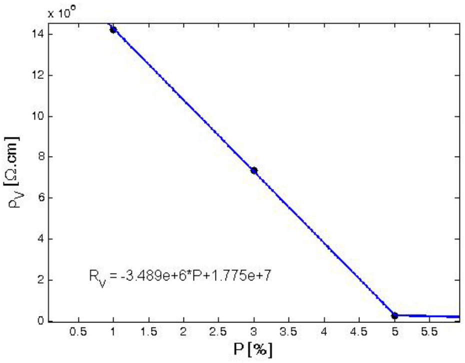


Fig. 5c. The dependence between volume resistivity and percentage of conductive phase in sample – below percolation threshold.

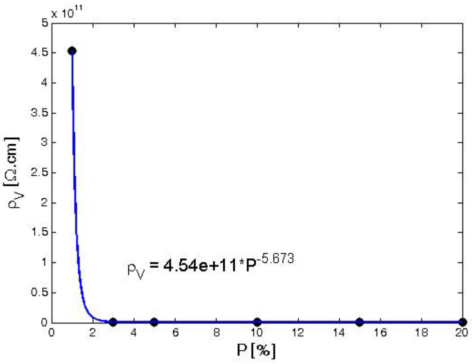


Fig. 6. The dependence between volume resistivity and percentage of conductive phase in hybrid yarn for samples 7-12.

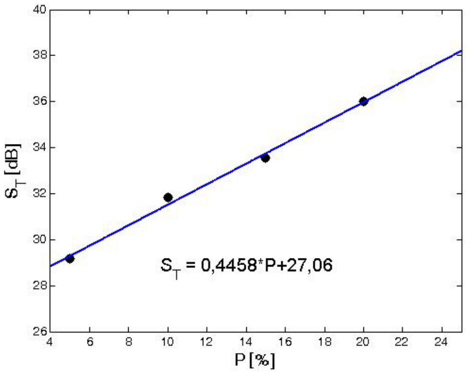


Fig. 7a. The dependence between S_T and percentage of conductive phase in sample for samples 1-6.

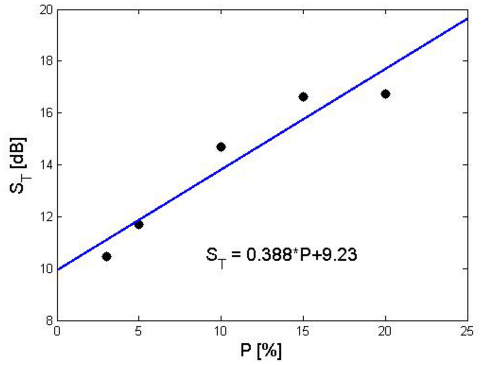


Fig. 7b. The dependence between S_T and percentage of conductive phase in sample for samples 7-12.

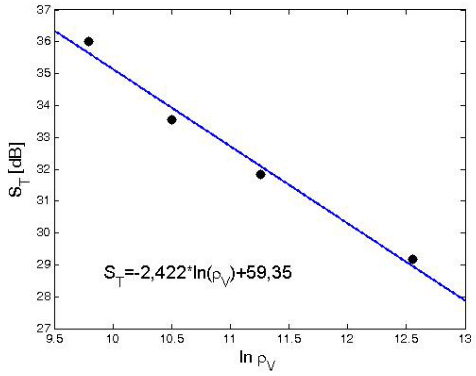


Fig. 8a. The dependence between total shielding effectiveness and logarithms of volume conductivity above percolation threshold $V_0$for samples 1-6.

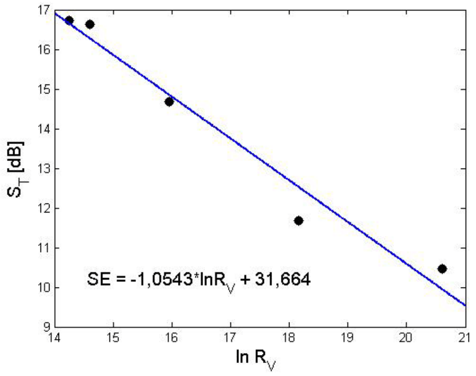


Fig. 8b. The dependence between total shielding effectiveness and percentage of conductive phase in hybrid yarn above percolation threshold V_0 for samples 7-12.

Sample	**Composition**	**Weave**	**Placement of hybrid**
1	99% POP/ 1% SS	twill 2/2	100%
2	97% POP/ 3% SS	twill 2/2	100%
3	95% POP/ 5% SS	twill 2/2	100%
4	90% POP/ 10% SS	twill 2/2	100%
5	85% POP/ 15% SS	twill 2/2	100%
6	80% POP/ 20% SS	twill 2/2	100%
7	99% POP/ 1% SS + 100% POP	twill 2/2	5x5 mm
8	97% POP/ 3% SS + 100% POP	twill 2/2	5x5 mm
9	95% POP/ 5% SS + 100% POP	twill 2/2	5x5 mm
10	90% POP/ 10% SS + 100% POP	Kepr 2/2	5x5 mm
11	85% POP/ 15% SS + 100% POP	Kepr 2/2	5x5 mm
12	80% POP/ 20% SS + 100% POP	Kepr 2/2	5x5 mm

Table. 1. Studied fabrics details.

Sample	**RV [kΩ cm]**	**ST [dB]**
1	1.424E+07	19.26
2	7.339E+06	26.69
3	2.840E+05	29.16
4	7.749E+04	31.83
5	3.642E+04	33.54
6	1.789E+04	36.02
7	4.54E+11	4.20
8	8.90E+08	10.47
9	7.69E+07	11.69
10	8.47E+06	14.69
11	2.21E+06	16.64
12	1.54E+06	16.72

Table 2. Mean values of ρ_V and shielding effectiveness S_T.

Material	**S_T [dB]**
100% carbon weave (190 g/m^2)	46.80
100% hybrid wave (80% POP/ 20% SS)	36.02
100% aluminum foil (30 g/m^2)	35.40
PET fabric/PPY composite	20.24
100% hybrid wave (99% POP/ 1% SS)	19.26
POP woven containing mesh 5x5 mm of hybrid yarn (80% POP/ 20% SS)	16.72
POP woven containing mesh 5x5 mm of hybrid yarn (99% POP/ 1% SS)	4.20

Table 3. S_T of various conductive fabrics at frequency 2,4 GHz.