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Effects of weaving structure and reduced graphene oxide application on electrical conductivity of woven fabrics

Seyda Eyupoglu[a]

Department of Textile, Clothing, Footwear and Leather, Vocational School of Technical Sciences, Istanbul University-Cerrahpasa, Istanbul, Turkey

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This paper reports a comprehensive evaluation of electrical conductivity characteristics of woven fabrics. Stainless steel weft yarn and polyester warp yarn have been selected to fabricate plain and twill woven fabrics with two different densities. In order to improve electrical conductivity characteristics of woven fabrics, the fabrics are treated with reduced graphene oxide. Electrical conductivity of samples is analyzed in accordance with fabric structure. Furthermore, the effect of reduced graphene oxide treatment on electrical conductivity of samples has also been investigated. The structural identification of samples is evaluated with Fourier transform infrared spectroscopy. The results indicate that the electrical conductivity of fabrics improves with increase in density, and weave structure also affects the electrical conductivity. After the reduced graphene oxide treatment, the electrical conductivity of samples improves. The optimum conductivity of 442.28 S/m, for high density plain weave fabric dipped in reduced graphene oxide, was recorded.

Keywords: Electrical conductivity, Polyester yarn, Reduced graphene oxide, Stainless steel yarn, Woven fabric

1 Introduction

Nowadays, the demand of wearable electronics has been growing owing to their potential applications in portable electronic devices, in multifunctional fabrics, including healthcare units and wearable displays. Currently, electronic gadgets, made by heavy weight metallic sheets and plastics, are being replaced by the lighter weight conductive textiles and their composites. The transformation of conventional electronics in wearable electronics led to enormous progress in the material science. Because of using a material in wearable electronics, in addition to high electrical conductivity, the material should have desirable mechanical and flexural properties[1]. A variety of flexible materials involve fibre fabrics, yarns, metal films, and papers which are utilized to prepare flexible electronic materials. Fabrics can be deemed as optimum material for electronic devices because of low cost, lightweight, high elasticity and strength. Despite all these optimum features, the practical application of textile materials in electronic devices is benefited by the electrical insulation nature of textile materials due to molecular structures. In order to improve electrical conductivity of these materials, many researchers used carbon materials[2].

[a]E-mail: seyda.eyupoglu@istanbul.edu.tr,
seyda.eyupoglu@iuc.edu.tr

Conductive textiles can be produced by different techniques such as adding conductive particles in the polymer before fibre extrusion, using metal yarns into the fabric production, and chemical metallization[3-5]; however, these techniques lead to reduce the flexibility of textile material. Conductive yarns can be produced from conductive metals, such as ferrous alloys, nickel, stainless steel, titanium, aluminum and copper. Although highly conductive, metallic fibre are expensive, brittle and heavier than most textile fibre, making it difficult to produce homogeneous blends, and leading to reduce the flexibility of textile material[6]. To overcome these disadvantages, functional finishing method has been popular in production of conductive textiles.

High specific surface area and porosity increase the chemical uptake ability as compared other substrates. High porosity is a disadvantage for electrical conductivity, because of air gap molecular, which reduces electrical conductivity. In literature, much research is reported to increase electrical conductivity of textile material. Govaret and Vanneste[7] developed conductive cotton and polyester fabrics coated with carbon nanotubes. Li *et al*.[8] produced a textile-based antenna with the use of copper nano particles. Yaghoubidoust *et al*.[9] coated cotton fabric with graphene oxide/polypyrrole to improve electrical conductivity of cotton fabrics. Berendjchi *et al*.[10]

firstly dipped polyester fabric in graphene oxide, after that in reduced graphene oxide and then filled the gap with polypyrrole. After this process, the electrical conductivity of polyester fabric improves. These electrically conductive textiles have been used in photovoltaic devices, supercapacitors, piezo-electric sensors, electromagnetic shielding applications, and energy storage[11,12]. Especially, many researchers have investigated the electromagnetic shielding effect of conductive fabrics produced with conductive yarns[13]. In addition, thermal fabrics, used in the areas of health care, medicine, sports and outdoor activities, can be fabricated with conductive yarns[14].

The discovery of graphene has become the focus of researchers in carbon material research. Graphene is 2-dimensional (2D) sheet of sp^2 carbon atoms in a honeycomb structure. Recently, it has become popular due to its many attractive properties, such as high electrical conductivity[15], mechanical strength[16], hydrophobic[17], high flexibility, thermal and chemical stability, and other remarkable properties[18]. The extraordinary properties of graphene make it useful in numerous areas, such as composites, energy storage, electrical conductivity, nano electronics, sensors, and biosensors[19]. However, the use of pristine graphene can lead to difficulties, as it causes agglomeration, and has poor solubility. For minimizing these difficulties, graphene oxide obtained by oxidation of graphene can be used as a substitute for graphene. Graphene oxide has hexagonal carbon structure as graphene; however, it contains hydroxyl (− OH), alkoxy (C−O−C), carbonyl (C=O), carboxylic acid (−COOH) and other oxygen based functional groups unlike graphene. Due to these oxygenated groups, graphene oxide has many characteristic properties, such as high solubility, electrical conductively, anti-ultraviolet, and water repellent[20].

The aim of this study is to obtain electrically conductive fabric (handloom woven) with polyester warp yarn and stainless steel weft yarn, which is then dipped in reduced graphene oxide. To the best of our knowledge, there is no other study available in literature on the above-mentioned new conductive fabric. The effects of weaving structure and reduced graphene oxide application on electrical conductivity of samples are investigated.

2 Materials and Methods

2.1 Materials

Stainless steel yarn was purchased from Technoart Company in Turkey. Polyester yarn was supplied from Korteks Company in Turkey. The characteristic properties of stainless steel and polyester yarns are given in Table 1.

2.2 Fabric Preparation

The woven fabrics, which were produced on a handloom, had plain and twill structures. In the weaving, polyester yarn was used as warp yarn and stainless steel yarn was used as weft yarn. Furthermore, the fabrics were weaved with two different densities. The properties of weaved fabrics are given in Table 2.

In order to measure mass per unit area, specimens of 100 mm × 100 mm size from the fabric samples were conditioned and weighted in an analytical balance under standard atmosphere conditions. Mass per unit area measurements of sample were iterated five times and average was calculated.

The thickness of fabric samples was measured with James heal thickness gauge. The measuring principle of thickness gauge is based in the measurement of the distance between the reference plate of the device and the parallel presser foot of the measuring device. The measurements of sample thickness were iterated five times and average was calculated.

Porosity of the fabric samples was calculated using following equation[21]:

$$P = \frac{100}{t} * [t - \left[\left(warp\ per\ cm * \frac{weight\ of\ warp\ yarn\ \left(\frac{g}{cm}\right)}{density\ of\ warp\ yarn}\right) + \left(weft\ per\ cm * \frac{weight\ of\ weft\ yarn\ \left(\frac{g}{cm}\right)}{density\ of\ weft\ yarn}\right)\right] \quad ...(1)$$

where P is the porosity; and t, the thickness of the fabric in cm.

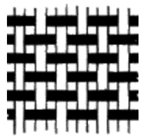
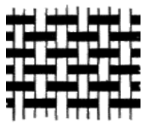
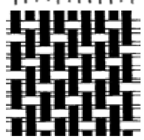
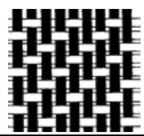
2.3 Reduced Graphene Oxide

Reduced graphene oxide is known as the form of graphene oxide which is manufactured by thermal, chemical, and other methods to reduce the oxygen

Table 1 — Characteristic properties of stainless steel and polyester yarns

Fibre type	Count tex	Fibre number	Diameter mm	Twist
Stainless steel	325	150	12	Z
Polyester	200	100	10	Z

Table 2 — Properties of weaved fabrics

Fabric code	Fabric construction	Structure	Mass per unit area g/cm^2	Warp density ends/cm	Weft density picks/cm	Thickness mm	Porosity
PW1	Plain weave		3.83	18	8	0.15	57.33
PW2	Plain weave		3.13	12	6	0.12	62.50
TW1	Twill weave		3.74	18	6	0.17	68.23
TW2	Twill weave		3.22	15	5	0.14	70.15

content. In this study, stainless steel yarn reinforced fabrics were dipped in reduced graphene oxide to improve electrical conductivity. Reduced graphene oxide was supplied from Grafenbiotech Nano Technology Engineering Company (Turkey). The properties of reduced graphene oxide are: 99.5 purity, 100 mg weight, 2-8 nm thickness, 400-500 m^2/g surface area, 25 µm surface width and chemical composition (65% carbon, 32% oxygen, 2% hydrogen, and 0.50% nitrogen).

2.4 Dipping of Reduced Graphene Oxide

Reduced graphene oxide was mixed with distilled water in 1:100 ratio using magnetic stirrer at 600 rpm for 3 h and a few drops of acetic acid was added to adjust *p*H at 5.5. After that, the fabric samples were dipped into the reduced graphene oxide suspension at room temp (23°±2°C) in ultrasonic bath for 30 min mixture. Finally, samples were dried in an oven at 80°C for 10 min.

2.5 Fourier Transform Infrared Spectroscopy Analysis

Fourier transform infrared (FTIR) spectrometer (Bruker Corporation, Massachusetts, USA) was utilized to determine the functional groups in the samples. The spectral scan was noted in the wave region of 400-4000 cm^{-1} at a rate of 32 scans per minutes. Each peak is assigned to a functional group in the samples.

2.6 Conductivity Measurement

A four-point probe method was used to measure electrical conductivity of samples. Electrical conductivity of samples was measured with an Agilent 4339B high resistance meter (Agilent Technologies Co., Ltd., USA) at 20°C and 65% RH. The electrical conductivities of the samples were calculated according to following equation:

$$\sigma = \frac{l.I}{d.w.V} \quad \text{... (2)}$$

where σ is the electrical conductivity (S/cm); *l,* the distance between probes (cm); *I*, the current (mA); *d,* the thickness (cm); *W*, the length of probe (cm); and *V*, the voltage (mV). Electrical conductivity measurements of sample were iterated five times and average was taken[22].

3 Results and Discussion

3.1 FTIR Analysis

The FTIR analysis graphs of PW$_1$, reduced graphene oxide, and reduced graphene oxide dipped PW$_1$ are given in Fig. 1.

In Fig. 1 (a), the absorption peak near 1700 cm^{-1} indicates the presence of C = O strech in the stainless steel and polyester yarn. The peaks at 1410 cm^{-1} and 1334 cm^{-1} relate to O = C = O streching of carbondioxide related with stainless steel yarn[23]. Furthermore, the peak at 1410 cm^{-1} correspod to aromatic ring of polyester yarn. The peaks near 1091 cm^{-1} and 1015 cm^{-1} indicate the presence of O = C − O − C. The peak at 862 cm^{-1} is assigned to five substituted H in benzene. The peaks at 760 cm^{-1} and

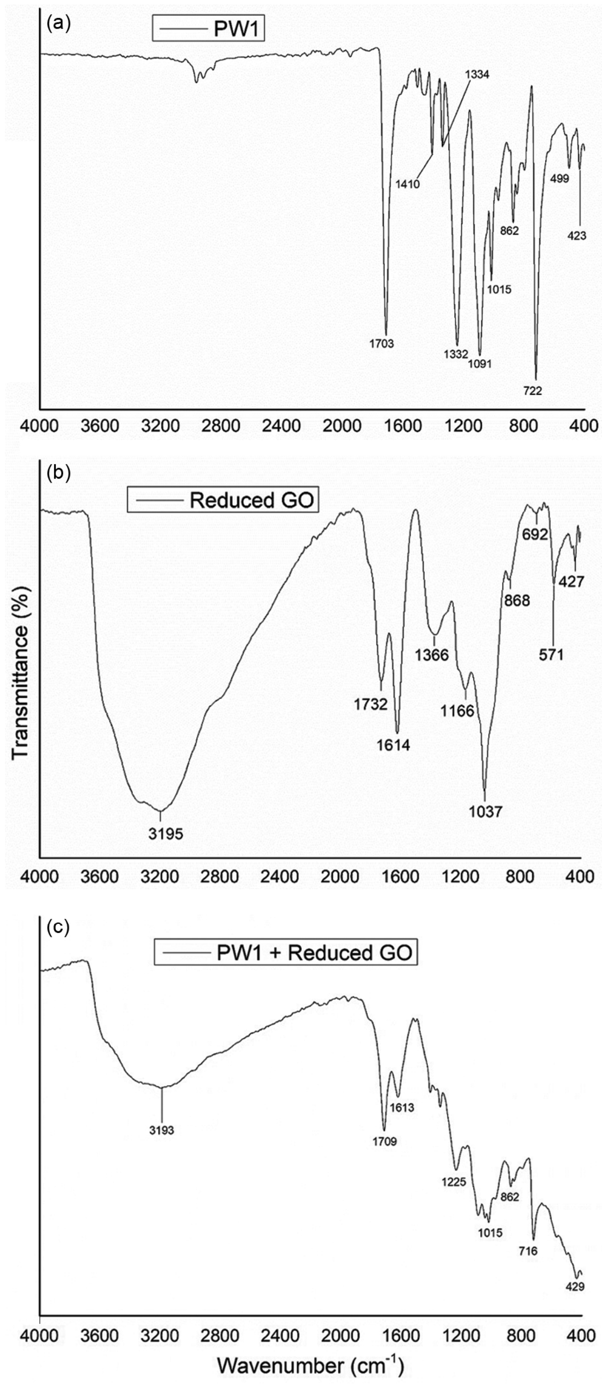


Fig. 1 — FTIR spectra of samples (a) PW_1, (b) reduced graphene oxide, and (c) reduced grapheme oxide dipped PW_1

400 cm^{-1} are attributed to the presence of C −C stretch corresponding to stainless steel yarn[24].

In Fig. 1 (b), the band near 3195 cm^{-1} is corresponding to O −H stretching vibration. A absorption peak is recorded at 1732 cm^{-1}, corresponding to C = O stretch mode in carboxyl group. The peak near 1614 cm^{-1} is assigned to the aromatic C = C bond. The peak at

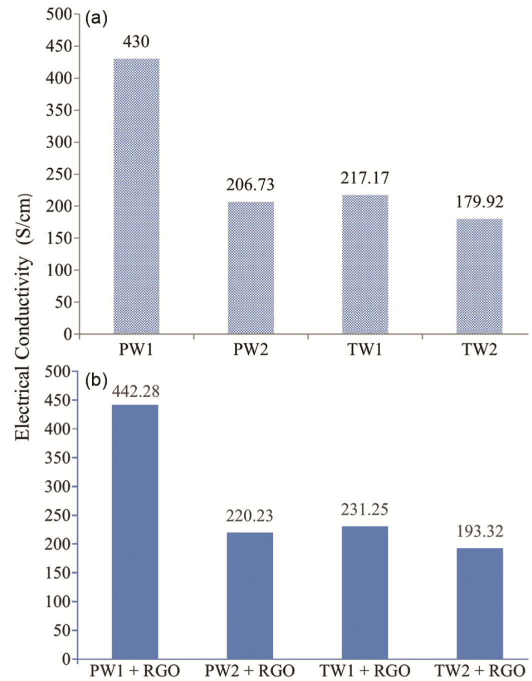


Fig. 2 — Electrical conductivity of samples (a) weaved fabrics and (b) samples applied with reduced graphene oxide

1366 cm^{-1} is arising due to C−OH carboxyl group. The peak at 1166 cm^{-1} is corresponding to the epoxy C−O stretching. An absorption peak is determined at 1035 cm^{-1}, corresponding to C−O stretching vibration in the alkoxy group. The peaks at 800 cm^{-1} and 400 cm^{-1} are assigned to the presence of C −C stretch. All mentioned bands are peaks of reduced graphene oxide[25].

In Fig. 1 (c), the peaks near 3193 cm^{-1}, 1709 cm^{-1}, and 1613 cm^{-1} indicate the presence of O −H stretching vibration, C = O stretch mode in carboxyl group, and aromatic C = C bond in reduced graphene oxide respectively. The peak at 1015 cm^{-1} is corresponding to O = C −O −C in polyester fibre. The peaks at 760 cm^{-1} and 400 cm^{-1} are assigned to C −C stretch corresponding to stainless steel yarn. These stretches indicate that reduced graphene oxide is dipped to the fabric samples which is produced from polyester warp and stainless steel weft yarn[23-25].

3.2 Conductivity Results

Electrical conductivity of materials can be defined as how much voltage is required to get an amount of electric current to flow. Figure 2 shows electrical conductivity of samples.

Electrical conductivity is one of the most important properties in electronic devices. Materials can be classified as metals, ceramics, polymers, composites, and semiconductors. Electrical conductivity mechanism of these materials differs from each other. The specific properties of metals include their high electrical conductivity due to the availability of free electrons and narrow band gap. Ceramics involve ionic and covalence bonds with moderate bandwidth. Polymers do not have any free electrons with high bandwidth[26]. Electrical conductivity is affected by the type of material, material construction, molecular structure and atomic configuration of material, total length, cross-sectional area and temperature. Metals have high electrical conductivity since valance electrons are in free form. Ionic and covalent bonded materials have low electrical conductivity since they do not contain free electrons[27].

In order to observe the effect of weave type on electrical conductivity values of the fabric samples, plain and twill weave fabric samples have been used and the results are shown in Fig. 2 (a). According to the results, the electrical conductivity of samples varies from the fabric construction. It is found that plain weave fabric sample having high density shows high electrical conductivity. In previous studies, it has been shown that higher electrical conductivity values are obtained in plain fabrics because of the fact that yarns are packed closer, and hence, the porosity of the fabric is reduced. Among all fabric weaves, plain weave provides the most strengthen construction owing to the more intersection points with warp and weft yarns. It is the only weave, wherein warp and weft yarn do not swim. Compared to twill weaves, plain weave structure is more compact. Furthermore, porosity of plain weave is higher than that of twill weave. Electrical conductivity results show that plain weave fabric has higher electrical conductivity compared to twill weave fabric. It is deemed that twill weave fabric has more porosity and as a result have more air molecules than plain weave fabric. As the electrical conductivity of air is much lower than that of steel and polyester, the air decreased the electrical conductivity of twill weave fabric. Furthermore, the study shows that, porosity is the major indicator for electrical conductivity of a fabric. A fabric with higher porosity represents that the fabric structure encompasses more void spaces or fabric pores. In the pores of a fabric, there are air molecules and the electrical resistivity of air ranges from $10^9 \Omega$ to 10^{15} Ω. In other words, air molecules in fabrics cause an increase in the electrical resistivity of fabric. Fabric construction is the major factor to determine the porosity. In addition, the fabric construction influences the pore size, pore distribution, pore connectivity and total pore volume, and all of these properties affect the porosity properties of a fabric[28]. Moreover, it is considered that the higher electrical conductivity value is obtained in plain weave fabric due to the fact that warp and weft yarns can be packed closer because of higher number of interlacing in meter; therefore, the porosity of the fabric reduces, and it results in higher electrical conductivity in plain weave fabric[29].

Table 3 — Comparison of electrical conductivity of some materials.

Material	Electrical conductivity S/cm	Reference
Reduced graphene oxide film	3.82×10^{-3}	29
Tetratiafulvalenetetrathiolate nickel	3×10^{-4}	30
Ethylenetetrathiolate nickel	6×10^{-5}	30
Butadienetetrathiolate nickel	3×10^{-8}	30
Cotton fabric coated with graphene oxide	10^{-1}	31
Polyester yarn dyed with carbon nanotube	10^{1}	32
Cu-Carbone nanotube	2×10^{5}	1
Au-Carbone nanotube	3×10^{5}	1
Graphane-coloured fabric	0.0108	33
Combined silver nanowires with cupro fabrics	109,89	34
Poly analine + polyester fabric + piny acid (30%)	2.15	35
Poly analine + cotton fabric + piny acid (30%)	2.28×10^{-2}	35
PW1 + RGO	442.28	Present study

When the electrical conductivity of samples is evaluated in accordance with warp and weft densities, it is found to be increased with increase in fabric density. This may be due to the fact that the warp and weft yarns can be packed closer and electrical conductivity rises with the decrease in the fabric porosity[29].

The electrical conductivity results of samples treated with reduced graphene oxide are given in Fig. 2 (b). After reduced graphene oxide application, the electrical conductivity of samples significantly increases. In literature, graphene is described as 2-dimensional (2D) sheet of sp^2 carbon atoms in a honeycomb structure. In addition, graphene oxide (GO) is obtained by oxidation of graphene, and it has attractive properties as compared to graphene in many applications. Due to its electronic configuration and atomic bonds, electrical conductivity is very as high compared to metals[15].

In literature, researchers have carried out many investigations related to electrical conductivity of different materials which were aimed to increase the electrical conductivity of samples[29-34]. Table 3 shows the comparison of electrical conductivity of some materials, and it can be seen that the sample having high electrical conductivity is (PW1+GO). Compared to other materials, the electrical conductivity of PW1+GO is promising.

4 Conclusion

The present study was aimed at preparing the electric conductive weaving fabrics using reduced graphene oxide. In order to increase the electrical conductivity of samples, all samples have been dipped in reduced graphene oxide. It is observed that the weaving parameters affect the electrical conductivity of samples. The electrical conductivity of samples is proportional to the porosity and the results show that porosity is major indicator for electrical conductivity of a fabric. In addition, reduced graphene oxide application causes improvement in electrical conductivity of samples.

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