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Fabricating electroconductive cotton textiles using graphene

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ABSTRACT

In this work, design parameters were investigated for enhancing the conductivity of graphene-coated cotton textiles. Graphene oxide (GO) was immobilized on cotton fabric through a conventional "dip and dry" method. The GO-coated fabrics were then immersed in an aqueous solution of reducing agent, which converted the GO into graphene. The effect of various parameters such as type of reducing agent ($NaBH_4$, N_2H_4, $C_6H_8O_6$, $Na_2S_2O_4$ and NaOH) and its concentration, reduction time and number of coating process on conductivity of the fabrics was studied. The mechanical performance of the fabrics was also investigated. The results showed that the best conductivity and mechanical performance were obtained using $Na_2S_2O_4$ as a reducing agent. The reaction time of 30 min at 95 °C was enough for complete reduction of the GO. Electrical conductivity increased by approximately three orders of magnitude with the increase in the number of coating process from 1 to 20 cycles.

1. Introduction

Flexible fibrous textile materials containing conductive fillers have recently attracted much attention for their use in a wide range of applications, especially in advanced composites and E-textiles (Cakir, 2011; Cherenack, Zysset, Kinkeldei, Münzenrieder, & Tröster, 2010; Mattila, 2006; Robert, Feller, & Castro, 2012; Shim, Chen, Doty, Xu, & Kotov, 2008; Tao, 2001; Yang, Lightner, & Dong, 2011). E-textiles are fabrics that enable computing, digital components and electronics to be embedded in them. Similar to classical electronics, construction of electronic capabilities on textile fibers requires use of conducting and semi-conducting materials. Electroconductive textiles can be made using metal strands or metallic fibers mixed with textile fibers woven into the construction of the textile. However, because both metals and classical semiconductors are stiff material, they are not very suitable for textile fiber applications since fibers are subjected to a high degree of stretch and bending during their application. There is also an interest in semiconducting textiles, made by impregnating normal textiles with intrinsically conducting polymers, carbon black, carbon nanotubes or metal-based powders (Babu, Dhandapani, Maruthamuthu, & Kulandainathan, 2012; Egami et al., 2011; Havel, Behler, Korneva, & Gogotsi, 2008; Little, Li, Cammarata, Broughton, & Mills, 2011; Negru, Buda, & Avram, 2012; Zhao, Cai, Zhou, & Fu, 2011). But, the most widely used methods require complex processes, expensive materials and pre-functionalization and have some disadvantages such as lacking uniform coating, flexibility and durable wear resistance, which increase cost of production.

Graphene is a flat monolayer of carbon atoms which is tightly packed into a two-dimensional honeycomb lattice and is a basic building block for graphitic materials of all other dimensionalities (Geim & Novoselov, 2007). Due to its outstanding electronic, optical, exitonic, thermal and mechanical properties, graphene differs from most conventional three-dimensional materials and has attracted great interest as an outstanding candidate for the production of advanced materials with many potentials in various applications (Allen, Tung, & Kaner, 2010; Bai & Shen, 2011; Huang et al., 2011; Rao, Sood, Subrahmanyam, & Govindaraj, 2009; Zhu et al., 2010). Graphene is more suitable for E-textiles because it can be conducting and semiconducting and applied as a dye to make electrically conducting textiles (Dong et al., 2012; Fugetsu, Sano, Yu, Mori, & Tanaka, 2010; Khan, Young, O'Neill, & Coleman, 2012; Shin et al., 2012; Yu et al., 2011). It has been demonstrated that aqueous dispersions of graphene can be readily produced without the need for polymeric or surfactant stabilizers due to the presence of carboxylic and hydroxyl groups. These advantages lead to the possible direct application of graphene in preparing electroconductive textiles using the same strategy that has been used to make textile finishing through simple dip-pad or dyeing assembly.

Graphene can be prepared in large quantities through chemical conversion from graphite, which has facilitated fabrication of graphene-based materials. Graphene oxide (GO) has been prepared by harsh oxidation using Hummer's method (Hummers & Offeman, 1958). The as-made GO obtained in this way is electrically insulating due to the attached oxygen functional groups. Consequently,

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various reduction methods such as thermal or chemical reduction have been developed to restore its electrical conductivity. Thermal reduction has been highly effective in producing graphene-like films. However, this approach is limited by the choice of substrate; i.e., typical textile substrates cannot be used due to their low degradation temperature. On the other hand, chemical reduction can be realized at the temperature lower than 100 °C, which is extremely important for practical applications. Many reducing agents with generally low cost have been developed by a simple method to reduce GO; but, the reduction mechanism by chemical reducing agents has been unclear and the electrical conductivity of the graphene film is very different. Therefore, it is necessary to develop a more effective chemical reduction method to produce graphene-based materials with high electrical conductivity.

In this paper, the fabrication of electroconductive cotton textiles was explored using graphene. GO was deposited on the surface of fabric through a conventional "dip and dry" approach. The GO loaded fabrics were then chemically reduced for conversion into the electroconductive graphene. The chemical reduction of GO with several reducing agents was examined to investigate their effect on conductivity of the fabric. Effect of reductant concentration, reduction time and the number of coating cycles were also investigated. Although numerous studies have investigated effect of reducing agent on electrical properties of graphene materials, this is the first report on the effect of reducing agent on electrical properties of graphene-coated textiles. The results are important for understanding and controlling electrical properties of graphene-coated textiles and their possible applications.

2. Experimental

2.1. Materials

Graphite purum powder (particle size < 100 μm) was purchased from Fluka. All other materials including hydrazine (N_2H_4), sodium borohydride ($NaBH_4$), sodium hydrosulfite ($Na_2S_2O_4$), sodium hydroxide (NaOH), ascorbic acid ($C_6H_8O_6$), potassium permanganate ($KMnO_4$), hydrogen peroxide (H_2O_2, 35%), sulfuric acid (H_2SO_4, 98%) and hydrochloric acid (HCl, 37%) were supplied by Merck. Desized, scoured and bleached 100% cotton fabric was used as the substrate. The water used in all the experiments was purified using a Milli-Q system with the resistivity of higher than 18.2 MΩ cm^{-1}.

2.2. Synthesis of GO

GO was synthesized from graphite powder by the modified Hummer's method (Hummers & Offeman, 1958). One gram of as-purchased graphite powder was added to 25 ml of H_2SO_4 (98%) and was left while stirring for 12 h. Afterwards, while keeping the temperature at less than 10 °C, 3.5 g of $KMnO_4$ was added. This was stirred at 50 °C for 2 h. Next, 70 ml of water and 5 ml of H_2O_2 were added and then the mixture was stirred for 30 min. For purification, the resulting mixture was centrifuged, rinsed first with 5% HCl and then three times with water. 200 ml of water was added to the resulting product to make 0.5% (w/w) dispersion. This 0.5% aqueous dispersion was used to prepare all of the subsequent dispersions for deposition.

2.3. Preparing GO-coated cotton fabric

Aqueous dispersion of GO with the concentration of 0.05% was prepared and bath-sonicated for 60 min. The cotton fabric was dipped into the prepared dispersion, soaked for 30 min at room temperature and then dried at 90 °C for 30 min. Because of the strong adsorption, the fabric was quickly coated by the GO. The coating process was repeated three times in order to increase GO adsorption.

2.4. Preparing graphene-coated cotton fabric

The GO-coated samples (1 g of each) were immersed in 100 ml aqueous solution of 25 mM reducing agents of $NaBH_4$, N_2H_4, $C_6H_8O_6$, $Na_2S_2O_4$ and NaOH. The mixture was kept at 95 °C for 60 min under constant stirring. The resulting fabric was washed with a large amount of water several times to remove the excessive reducing agents. At the end, the samples were dried at 90 °C for 30 min. The resulting graphene-coated fabrics were referred to as $NaBH_4$–GO–cotton, N_2H_4–GO–cotton, $C_6H_8O_6$–GO–cotton, $Na_2S_2O_4$–GO–cotton and NaOH–GO–cotton based on the used reducing agents.

2.5. Characterization

Transmission electron microscopy characterization of the GO nanosheets was performed using a microscope LEO 912AB. A droplet of GO dispersion was cast onto a TEM copper grid and the solvent was evaporated overnight at room temperature. Surface morphology of the fabrics was examined by a KYKY-EM3200 scanning electron microscope after sputter coating with a very thin layer of Au. The ultraviolet–visible (UV–vis) reflectance spectra of the fabrics were recorded on a Lambda 35 UV–vis spectrometer (Perkin Elmer Instruments Co. Ltd., USA). Color coordinates were determined by color measurement software using the CIE L^* a^* b^* color space at D65/10°. Electrical surface resistivity of the fabrics was measured using a standard two-probe method (Petersen, Helmer, Pate, & Eichhoff, 2011) by means of Sa-Iran digital multimeter model 8515. Tensile strength and elongation of the samples were evaluated using a MESDAN LAB instrument according to the standard test method of ISO 5081 (strip method). The constant cross-speed of approximately 50 mm min^{-1} was used throughout the experiments. The measurements were performed in the warp direction of fabrics and average values were obtained from measurements of four samples. The amount of GO deposited on fabric was determined by reweighing fabrics after drying for 1.5 h in an oven at 80 °C. An analytical balance (Scatec SBA32) with 10^{-4} precision was used to measure the samples' weights. Abrasion resistance was measured according to ASTM D4966-98. The end point was reached when two yarns were broken.

3. Results and discussion

Since cellulosic substrates have low stability at high temperatures and degrade quickly, using thermal methods, which produce graphene with high electrical conductivity, is not possible for the reduction of GO-coated cotton textiles. On the other hand, despite the possibility of graphene preparation via thermal reduction methods, this method cannot be used not only because of the limitations such as high price and nanosheets aggregation but also for low adsorption of graphene to cellulosic fabrics (lack of surface functionality and hydrophobicity nature of graphene). Therefore, it seems that covering the fabrics with GO and subsequently reduction treatment through low-temperature chemical methods can be a highly effective method.

GO was synthesized from natural graphite using Hummer's method that derivatize graphene sheets with carboxyl, carbonyl, hydroxyl and epoxide groups, thereby, breaking the p-conjugation in the two-dimensional carbon networks (Li et al., 2011; Park et al., 2008). The resulting product of GO powder was water dispersible, insulating and light brown in color. Fig. 1 shows TEM micrograph of a typical GO nanosheet deposited on a standard TEM grid. The sheet was several micrometers in dimension with the wrinkled (rough)

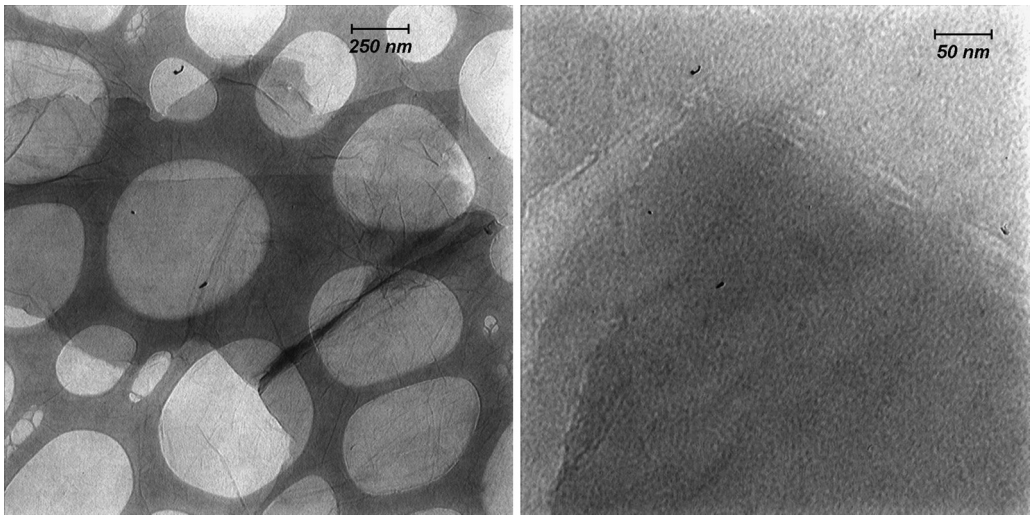

Fig. 1. TEM micrograph of a typical GO nanosheet; the micrograph on the right is in high-resolution.

surface texture. High-resolution TEM micrograph clearly illustrated the amorphous nature of the GO nanosheet.

The present approach for making electroconductive graphene-coated cotton fabric included two steps. The first was to coat cotton fabric with GO by a simple "dip and dry" method. The second was reduction of the GO deposited on the fabric to create electroconductive cotton fabric. When the cotton fabric was dipped into the GO dispersion, it was quickly coated with GO because of van der Waals forces between exfoliated GO, which has various functional groups such as carboxyl, carbonyl and hydroxyl, epoxy groups and cotton fibers. For the fabric used in this study, one gram of fabric could uptake about 2.5 mg of the GO. The SEM micrographs of the GO-coated fabric are shown in Fig. 2. It can be seen that, after coating fabric with GO, the inherence morphological structures of the cotton fibers did not change which was due to very low thickness and size uniformity of GO nanosheets that homogeneously coated the fibers surface. However, as indicated by arrows, a few white spots can be observed in some parts of the fiber due to incomplete exfoliation of graphite particles during synthesis process.

As SEM micrographs showed the GO nanosheets were uniformly coated on the fabric surface. For the conversion of insulating GO-coated fabric into an electroconductive substrate, the GO should be chemically reduced. Previous studies have demonstrated that type of reducing agent has substantial influence on the electrical properties of graphene. Hence, five different reducing agents, namely $NaBH_4$, N_2H_4, $C_6H_8O_6$, $Na_2S_2O_4$ and NaOH, were used for the reduction of the immobilized GO on the fabric in order to investigate their effect on conductivity of the cotton fabric.

As, in particular, color can be potentially employed as a fast and intuitive way for easy detection and simple evaluation of deposition and reduction of GO, color changes of the treated fabrics were investigated by assessing reflectance spectra and color coordinates. The reflectance spectra of the original, GO-coated and graphene-coated cotton fabrics in the ranges of 400–700 nm are given in Fig. 3. The original cotton fabric changed its color from white to yellow-brown due to the brownish color of the GO dispersion. After chemical reduction, color of the fabric changed from yellow-brown to graphitic black, which indicated removal of the oxygen functionalities and restoration of the graphitic structure during reduction treatment (Jung, Rhyee, Son, Ruoff, & Rhee, 2011). The reflectance spectra showed that the graphene-coated fabrics were close to each other in color; however, they were a little different. Reflectance percentage of the graphene-coated fabrics dropped as follows: $NaBH_4$–cotton, KOH–cotton, N_2H_4–cotton, $C_6H_8O_6$–cotton and $Na_2S_2O_4$–cotton in this order. The CIE color coordinates (L^* a^* b^*) and color differences (ΔE), quantitatively characterizing the observed color of the fabrics, are given in Table 1. The obtained results indicated darker color of the GO–cotton and graphene–cotton fabrics compared with the original fabric. The L^* values of the treated fabrics were lower than that of the original fabric. The GO–cotton fabric showed strong increase in the yellow color component (increased value of b^*)

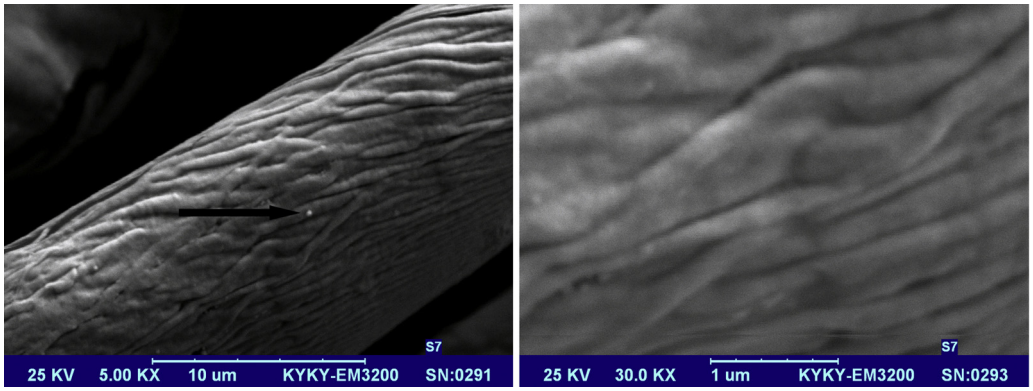

Fig. 2. SEM micrograph of the GO–cotton fabric showing a large-scale view of cotton fibers (left); high-magnification micrograph showing the uniform coating of GO nanosheets on the surface of cotton fibers (right).

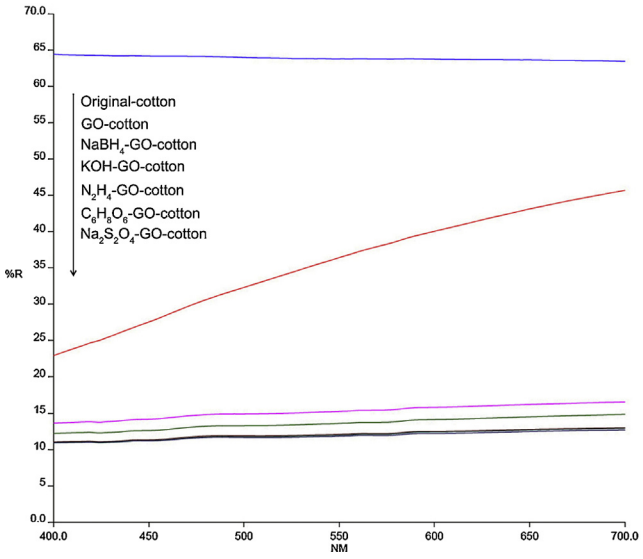

Fig. 3. Reflectance spectra of the original, GO–cotton and graphene–cotton fabrics.

Table 1
Color coordinates (CIE L^* a^* b^*) and color differences (ΔE) of the original, GO–cotton and graphene–cotton fabrics.

Sample	L^*	a^*	b^*	ΔE
Original-cotton	83.90	−0.11	−0.26	–
GO–cotton	66.75	2.22	12.09	21.26
$NaBH_4$–GO–cotton	46.02	0.45	2.48	37.98
NaOH–GO–cotton	43.71	0.47	2.41	40.28
N_2H_4–GO–cotton	41.43	0.35	2.00	42.53
$C_6H_8O_6$–GO–cotton	41.28	0.41	2.10	42.69
$Na_2S_2O_4$–GO–cotton	41.03	0.39	1.72	42.92

and in the red color component (increased value of a^*), which indicated a color change from white to yellow-brown. In addition, the ΔE values demonstrated visible color difference between the GO–cotton and the graphene–cotton fabrics. The ΔE values clearly showed no visible color difference between the N_2H_4–GO–cotton, $C_6H_8O_6$–GO–cotton and $Na_2S_2O_4$–GO–cotton fabrics (total color difference of one ΔE unit corresponding to the difference only noticeable by eye), which demonstrated reduction treatment by N_2H_4, $C_6H_8O_6$ and $Na_2S_2O_4$ did not have a substantial effect on the final color of the fabric. In conclusion, the obtained data from the reflectance spectra and the color coordinates simultaneously showed the successful incorporation and reduction of the GO on the cotton fabric. The color change was related to the reducing agent which caused removal of oxygen functionalities from the GO-coated cotton fabrics.

The electrical conductivity is perhaps the best indicator of the extent to which the GO has been reduced to graphene (Khan et al., 2012). The surface resistivity of the fabrics was measured by two probe method and the obtained data are presented in Table 2. Since GO lacked an extended π-conjugated orbital system, the GO–cotton fabric was not electroconductive. After reduction treatment, the

Table 2
Surface resistance of the GO–cotton fabric, after treatment with the reducing agents of $NaBH_4$, NaOH, N_2H_4, $Na_2S_2O_4$ and $C_6H_8O_6$.

Sample	Surface resistance ($k\Omega\,cm^{-1}$)
$NaBH_4$–GO–cotton	34,600
NaOH–GO–cotton	23,300
N_2H_4–GO–cotton	62.7
$C_6H_8O_6$–GO–cotton	31.2
$Na_2S_2O_4$–GO–cotton	19.4

Table 3
Tensile strength and elongation of the original, the GO–cotton and the graphene–cotton fabrics.

Sample	Tensile strength (N)	Elongation (%)
Original-cotton	166.3 ± 12.1	26.7 ± 0.6
GO–cotton	162.9 ± 12.2	28.4 ± 1.1
$NaBH_4$–GO–cotton	157.1 ± 12.7	27.1 ± 0.8
NaOH–GO–cotton	150.2 ± 5.1	27.1 ± 0.5
N_2H_4–GO–cotton	162.2 ± 5.3	28.3 ± 0.6
$C_6H_8O_6$–GO–cotton	141.7 ± 5.5	26.9 ± 0.4
$Na_2S_2O_4$–GO–cotton	162.0 ± 10.6	28.3 ± 0.1

surface resistance of the GO–cotton samples was reduced, indicating partial restoration of conjugation. The results showed considerable effect of the type of reducing agent on electrical conductivity. The electrical conductivity increased by approximately three orders of magnitude through changing type of the reducing agent. Restoration of the π-conjugated structure was the most effective using $Na_2S_2O_4$ and $C_6H_8O_6$ (resistance values of 19.4 and 31.2 $k\Omega\,cm^{-1}$, respectively), intermediately effective for reduction with N_2H_4 (62.7 $k\Omega\,cm^{-1}$) and relatively inefficient with KOH and $NaBH_4$ (23,300 and 34,600 $k\Omega\,cm^{-1}$, respectively). Such a result was consistent with the one obtained by color measurements, supporting the idea that chemical reduction under different reducing agents had substantial influence on electrical conductivity of the graphene-coated fabrics. The results showed that $Na_2S_2O_4$ was the best reducing agent for achieving a high level of electrical conductivity for GO-coated textiles. According to the proposed mechanism by Zhou et al. (2010), $Na_2S_2O_4$ is an efficient reducing agent because of its low electrode potential ($E^{\theta}SO_3^{-2}/S_2O_4^{-2} = -1.12$ V) in alkaline solution, easy dissociation of two protons and becoming a nucleophile. When epoxide and hydroxyl groups of the GO are attacked by a nucleophile with a back-side S_N2 nucleophile reaction, H_2O is released and results in the formation of an intermediate. Finally, thermal elimination leads to the formation of graphene, and the reducing agent ($S_2O_4^{-2}$) is oxidized to sulfite (SO_3^{-2}).

Stability of the mechanical properties of textiles in the finishing process is an important factor for practical applications. Textile performance of the modified cotton fabrics were evaluated in terms of mechanical properties. Tensile strength and elongation of the original, GO-coated and graphene-coated fabrics were measured and the results are presented in Table 3. In comparison with the original cotton, tensile strength of the GO-coated fabric slightly decreased. After chemical reduction, tensile strength of the fabrics treated with $NaBH_4$, N_2H_4 and $Na_2S_2O_4$ was very similar to that of the GO-coated fabric. However, significant decrease was observed in tensile strength of the fabrics treated with KOH and $C_6H_8O_6$. The results demonstrated that the reduction reaction under different reducing agents affected cellulosic structures of the cotton fibers. The observed change in the mechanical behavior of the samples treated with $NaBH_4$, N_2H_4 and $Na_2S_2O_4$ was in a range that was acceptable for standard cotton fabrics. With regard to the results of surface resistance and mechanical properties, it can be concluded that reduction treatment of the GO-coated fabric by $Na_2S_2O_4$ did not cause any damage to the structure of cotton fibers, which confirmed its suitability for practical applications. In addition, considering the large scale production, low price and its application in textile industry, especially in some industrial dyeing processes, $Na_2S_2O_4$ has a high potential for mass production of the electroconductive graphene-coated cotton textiles.

The influence of $Na_2S_2O_4$ concentration on conductivity of the graphene-coated fabric was investigated and the obtained results are reported in Table 4. It is obvious that the low concentration of $Na_2S_2O_4$ (0.1 and 0.5 mM) solution could not provide conductivity. In fact, these low concentrations did not remove enough oxygen-functional groups of GO for its conversion into electroconductive

Table 4
Effect of the concentration of $Na_2S_2O_4$ solution (0.1–100 mM), reaction time (1–120 min) and different cycles of dipping–drying coating (1–20) on surface resistance of the graphene–cotton fabric.

Parameter	Surface resistance (kΩ cm^{-1})
Concentration of $Na_2S_2O_4$ (mM)	
0.1	–
0.5	–
2.5	130.6
10.0	20.1
25.0	23.6
50.0	17.5
100.0	19.0
Reaction time (min)	
1	527.7
5	52.0
15	42.1
30	25.7
60	42.6
120	30.6
Cycles of process (times)	
1	201.1
4	3.87
7	1.73
10	1.27
15	0.757
20	0.374

graphene. The conductivity response markedly decreased with increasing $Na_2S_2O_4$ concentration from 2.5 to 10.0 mM (resistance decrease from 130.6 to 20.1 kΩ cm^{-1}, respectively). Afterward, $Na_2S_2O_4$ concentration up to 100.0 mM did not greatly influence response and only a little change was observed. However, the highest conductivity response was observed at concentration of 50.0 mM.

The effect of reduction time on conductivity response was also studied (Table 4). The data showed that, with the increase in reaction time from 1 to 30 min, surface resistance decreased (conductivity increased). The substantial decrease of resistance from 1 to 5 min, 527.7 to 52.0 kΩ cm^{-1}, respectively, demonstrated rapid removal of the most oxygen-functional groups of GO during the first stages of reduction. However, for the samples treated at 60 and 120 min, surface resistance slightly increased, which may be due to removal of some graphene nanosheets from surface of the fabric. It seems that the reduction reaction at 30 min was enough for complete reduction of GO and its conversion into electroconductive graphene.

Increase in the number of coating process can result in significant improvement in loading of GO and thus increase electrical conductivity of graphene-coated fabric. Fig. 4 presents digital photographs and the correspondence reflectance spectra of different cycles of GO-coated fabrics, which shows the changes in color of the fabrics in the wavelength range from 375 to 700 nm. As expected, percentage reflectance of the GO-coated fabric decreased as the number of process increased, which was consistent with the digital photographs. After chemical reduction, surface resistance of the graphene-coated fabric as a function of dipping–drying cycles was determined. The surface resistance of the fabric decreased with the number of dipping-drying coating processes and, consequently, electrical properties of the graphene-coated fabric could be easily controlled. Electrical conductivity increased by approximately three orders of magnitude after 20 dipping-drying cycles. In general, electrical conductivity increases with increasing the graphene content of the substrate, which can be attributed to improved orientation and structure of the graphene layer. A remarkably low surface resistance value of 0.374 kΩ cm^{-1} of the graphene-coated fabric could be attributed to the effective recovery of the sp^2 network of carbon via chemical reduction and good graphene sheet-to-sheet connection on the fabric surface.

The obtained graphene-coated fabrics were very flexible and graphene layer is not brittle and could not easily cracks under bending stress. For assessing wear resistance of the fabrics, abrasion resistance of one coated sample was measured by Martindale method. After abrasion, surface resistance of the graphene-coated fabric increased only from 1.7 to 2.6 kΩ cm^{-1}. The small decrease in surface conductivity demonstrated high wear resistance of graphene-coated cotton fabrics.

Graphene has advantages over other conductive materials such as carbon nanotubes and conductive polymers in terms of the fabrication of electroconductive textiles. These advantages include easy

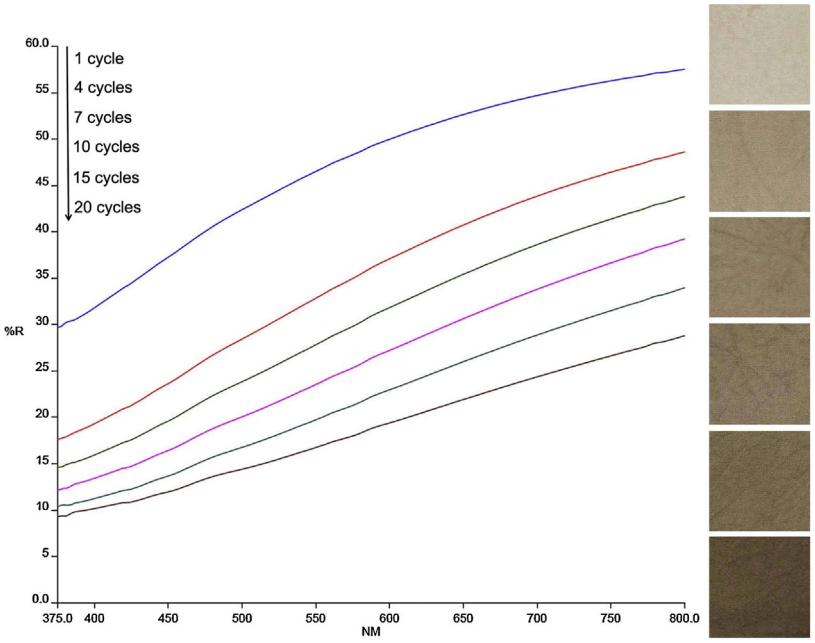

Fig. 4. Variation of reflectance spectra of GO–cotton fabric with different cycles of dipping–drying coating; 1, 4, 7, 10, 15 and 20 cycles. The images on the right are their correspondence digital photographs.

preparation, low cost, high specific surface area, and rough and wrinkled surface and unique flexible two-dimensional geometry. In addition, graphene has high affinity to the common textile material such as cotton and polyester whereas, for the high density and uniform coating of carbon nanotubes and conductive polymer, a special pretreatment, i.e., surface modification or surface functionalization, is needed which diminishes their large-scale applications. The efficiency of graphene in enhancing conductivity of the textile materials is equal or even much better than that of carbon nanotubes and conductive polymers. Also, conductivity of the graphene-coated fabrics could be simply tailored by changing the number of coating cycles.

4. Conclusions

Electroconductive cotton textiles were successfully prepared using graphene. GO nanosheets were deposited on the cotton fibers via "dip and dry" method followed by chemical reduction which caused their conversion into conductive graphene. Color of the fabric changed from white to light-brown and then to graphitic black as a results of coating with the GO and graphene. SEM micrographs showed that the GO nanosheets were homogeneously covered on the cotton fibers. The surface conductivity essentially depended on the type of reducing agents as the value of the electrical resistivity ranging from 10^3 to 10^6 kΩ cm^{-1} was obtained. $Na_2S_2O_4$ was determined to be the best reducing agent for achieving high level of electrical conductivity and 30 min reaction was enough for complete reduction of graphene oxide. Increasing the number of coating process could result in significant improvement in loading of GO and thus increase in electrical conductivity of the graphene-coated fabric. Considering low cost, easy preparation, simple and effective coating, these electroconductive fabrics are expected to have high potential for being used in advanced applications such as smart and E-textiles.

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