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Evaluation of the Electromagnetic Shielding Effectiveness of Carbon-Based Screen Printed Polyester Fabrics

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Abstract: Electromagnetic shielding has a very emerging role in the textile applications. Screen-printing is a well-known, easy and cost effective process for textile printing. In this study, carbon black and graphite particles were used to impart electromagnetic shielding property to polyester fabric by screen printing technique. To this aim, printing pastes containing carbon materials were prepared with different binder concentrations. The electrical resistance, surface morphology, color coordinates and washing fastness properties of screen printed polyester fabrics were investigated. The washing durability of electromagnetic shielding effectiveness of carbon based printed fabrics as a function of binder concentration have also been studied. Electromagnetic shielding effectiveness was evaluated in the frequency ranges between 15-3000 MHz. The results showed that the electromagnetic shielding properties of fabric were affected by increased binder concentration. The most durable electromagnetic shielding effectiveness after washing process was obtained at highest binder concentration. The surface morphologies and color difference values of printed fabrics after washing process also provided a positive contribution.

Keywords: Electromagnetic shielding, Textile, Screen printing, Carbon black, Graphite

Introduction

Electromagnetic interference (EMI) is a new form of pollution discovered in recent years [1]. EMI is a conducted and/or radiated electromagnetic signal. The source of electromagnetic interference can be any device or apparatus that transmits, distributes, processes or utilizes any form of electrical energy. EMI may intentionally or unintentionally react with either electronic devices, causing a degradation of performance of other equipment, or systems that share the same environment [2,3]. EMI is also harmful to human health and can even affect the human body under certain circumstances. Many diseases such as leukemia, miscarriages, breast cancer, are correlated to continuous exposure to electromagnetic radiation. Therefore, efforts were made to reduce its effect using electromagnetic shielding materials [4-6].

The shielding effectiveness (SE) is the ratio of the power received with and without a material present for the same incident power. It is expressed in units of decibels (dB), as shown in equation (1) [5,7].

$$SE = 10 \log(P1/P2) \quad (1)$$

where $P1$ is the received power with the material present and $P2$ is the received power without the material present.

Textiles are intrinsically non electromagnetic (EM) shielding materials and are rather insulating materials; however, they can successfully turn to be EM shielding after raw-material changes, new production process or process adaptations that make them electrically conductive. Some of the methods to obtain conductive fabrics are the use of metallic fibers and yarns, such as stainless steel, aluminum or copper yarns [8, 9]; however, these types of yarns tend to have low flexibility due to their large diameter, which produces a heavier, stiffer and uncomfortable fabric. Conductive fabrics can also be produced by conductive yarns with the use of conductive fillers or coatings incorporated in the yarn production. These processes are based on mixing the fiber polymer with fillers during their production processes such as melt or wet spinning [10,11]; or by twisting and wrapping a synthetic fiber with metallic yarns using mechanical spinning processes [11,12]. The yarn coating approaches are mainly in situ polymerization or plating techniques [6,13,14]. These coating technologies are less often used due to their inherent complexities. In general, the above techniques are time-consuming, complex and require the utilization and know-how of the whole textile supply-chain [15]. Other approaches to develop conductive fabrics include the application of conductive materials on the surface of the fabric itself using coating and printing techniques. Screen printing is the thick film process which is a simple and low-cost process [16]. Screen printing is also compatible with industrial processes, offering a route to high volume batch fabrication. Besides, the screen printing technique can be applied on any textile surface that can offers significantly more design freedom and placement capability on fabrics than other methods like weaving and knitting [17]. In the literature, there are many studies concerning about conductive carbon fillers in order to produce an electrically conductive, shielding material. For example, carbon black, carbon fibers, carbon nanotubes have been extremely used [18-21]. Carbon materials have outstanding advantages for this application due to their high conductivity, low weight, flexibility, environmental and thermal stability [22,23]. Carbon materials have been intensively tested for EM shielding applications; however, mainly for the fabrication of composite for higher frequency

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applications (X-Band and Ku-Band) and not for producing EM shielding fabrics [22,24-28]. In the present study, the electromagnetic shielding effectiveness was evaluated in the frequency ranges between 15-3000 MHz and the standard ASTM method (ASTM D4935-10) was used for assessing EM shielding fabrics. Frequencies between 100 kHz-300 GHz is named as radio frequency (RF) [29]. RF contains FM/AM radio, wireless phone, cellular phone, and computer [30,31]. Electromagnetic wave sources surrounding the human in daily life emit radiation in 800 MHz-3 GHz frequency range. Specifically, mobile phones emitting radiation in 900-1800 MHz frequency range, microwave ovens in 2450 MHz, radar systems in 1-10000 MHz, radios in 30-300 MHz frequency range can be given as example to the mentioned electromagnetic wave sources [32].

The aim of this study was to develop a production method for carbon-based screen-printed textiles for electromagnetic shielding applications. The screen printing technology is a well-established technology and potentially ideal for this application as it does not require complicated or expensive equipment and the printing process is simple, rapid and is easy to automate [33,34]. The screen printing method is fast way to obtain light-weight conductive textiles [35]. Binders play an important role in the case of screen printing. In order to examine the influence of binder concentration especially on electromagnetic shielding effectiveness, printing pastes containing different binder concentrations were prepared. For this purpose, printing pastes containing carbon materials were prepared with different binder concentrations. Surface morphology, color coordinates, washing fastness and electrical properties of screen printed polyester fabrics were investigated. The washing durability of electromagnetic shielding effectiveness of carbon based printed fabrics as a function of binder concentration have also been studied.

Experimental

Sample Preparation and Screen Printing

Carbon black (CB, Vulcan XC 72R) and graphite flakes (G, Sigma-Aldrich) were used to prepare conductive printing paste. Conductive carbon filler content was fixed at 15 wt% and applied on 100 % polyester fabric using screen printing technique.

Printing paste was prepared according to the procedure described in [36] as follows: (i) predetermined amount of CB and G were mixed with 1 m*l* acetic acid and grinded in a mortar for 5 min, (ii) 5 m*l* distilled water was added to the mixture and grinded for 5 min, (iii) 30 m*l* ethanol was added within 5 min during grinding, (iv) the mixture was then transferred to a beaker containing 100 m*l* ethanol, (v) the mixture was stirred with a magnet for 2 min and then horn sonicated for 2 min, this prosess was repeated 5 times (vi) 30 g of Terpineol was added to the mixture and step (v) repeated, (vii) during this time, the ethyl cellulose polymer based thickener (Ethocel, DOW) was dissolved at ethanol at 50 °, (viii) the thickener was added to the carbon mixture and step (v) repeated, (ix) the mixture was placed to the rotary evaporator to evaporate the ethanol. Printing paste was prepared with addition of different amounts of butadiene-styrene based binder (0, 10, 20 and 40 %wt) to the mixture. The carbon-based paste was then printed using a commercial screen printer (ATP04 Chest Printing Unit, Ata Makina, Turkey) through a fine porous mesh onto the polyester fabric. After printing, the prints were cured at laboratory type stenter (ATC-GK40, Ata Makine, Turkey) at 160 °C for 10 minutes.

Characterization

The surface morphologies of the printed carbon materials are characterized by scanning electron microscopy (SEM, FEI SIRION). To examine the accurate thickness of the carbon-printed layer on polyester fabric, an electronic micrometer (Mitutoyo) was used. To calculate the thickness value, thickness was measured from ten different places and then the difference between unprinted and printed fabrics was used to calculate the printed layer thickness of carbon nanomaterial printed fabrics. The color measurements were performed by Datacolor SF600+, using SAV aperture and SI mode, and the color differences were calculated in accordance with the CIELab system with D65/10 ° Observer values. In CIE Lab system, the lightness L^* represents the darkest black at L^*=0 and the brightest white at L^*=100, a^* represents redness (a^* is +)/greenness (a^* is -) and b^* represents yellowness (b^* is +)/blueness (b^* is -). a^* and b^* represent true neutral gray values at a^*=0 and b^*=0. The color difference (ΔE) was determined using equation (2):

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (2)$$

Washing fastness and staining were done according to ISO 105-C06. A grey scale is used for evaluating the results (1 is the worst and 5 is the best).

Electrical Resistance Measurement

The electrical properties of the screen printed samples were measured with the four-point method. The setup consists of a sourcemeter (Keithley 2450 Sourcemeter) and a four point probe station (Everbeing Int'l Corp). this is an electrical impedance measuring technique that uses separate pairs of current-carrying and voltage-sensing electrodes to improve accuracy [35]. The current I is fed through the outer contacts and the voltage V is measured across the inner electrodes, as shown in Figure 1.

The sheet resistance (Ω/sq) is calculated by [37];

$$Rs = R_{avg} \cdot C \quad (3)$$

where, Rs is the sheet resistance (Ω/sq), R_{avg} is the average resistance, C is the correction factor.

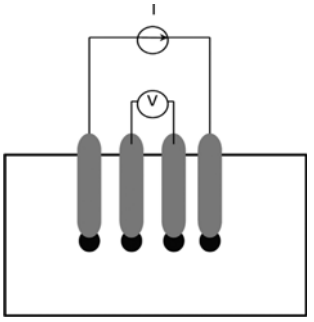

Figure 1. Four point probe schematics.

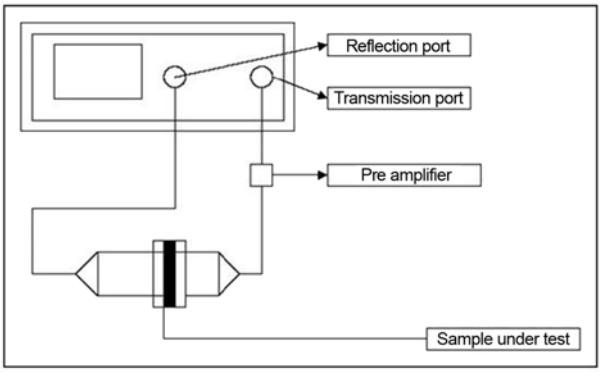

Figure 2. A typical coaxial transmitter for EMSE testing.

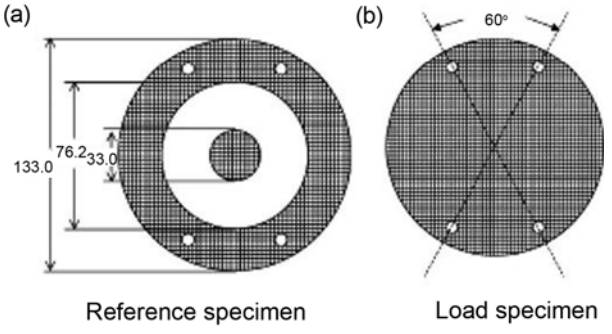

Figure 3. Specimen dimension for reference (left) and load test (right) ASTM D4935 (unit: mm).

EMSE Measurement

Electromagnetic shielding properties of screen printed cotton fabrics were tested based on ASTM D4935-10 the coaxial transmission line method for planar materials standard (Figure 2). A shielding effectiveness test fixture was used to hold the sample with a network analyzer generating and receiving the EM signals (Rohde&Schwarz ZVL-Network Analyzer). The ASTM D4935-10 Standard determined the shielding effectiveness of the textile structures using the insertion-loss method (Figure 3). The frequencies used in the SE testing were between 15 and 3000 MHz.

Results and Discussion

The Effect of Binder Concentration on Print Thickness

The effect of binder concentration and washing process on the print thickness of fabrics is given in Figure 4. It can be seen that the thickness of the fabrics increased with the increasing of binder concentration. As it is clearly seen, the as-printed fabric without binder has the lowest print thickness with the value of 86 μm while the fabric with 40 % binder has the highest print thickness with the value of 192 μm. The increment in the print thickness can be explained with the increasing of binder concentration increases the viscosity of the printing paste. However, it can be said that all printed fabrics have relatively lower thickness compared with [2,38,39]. After washing process, the print thickness of the fabrics decreased. The highest decrease was obtained at the fabric without binder with the proportion of 35 %. The printed fabric without binder has the lowest durability to washing. The most durable fabrics to washing were observed at fabrics printed with 10 % and 20 % binder concentrations.

Electrical Resistance Results

Electrical conductivity is one of the important criteria for electromagnetic shielding shielding because electromagnetic shielding materials need mobile charge carriers or holes [40]. Sheet resistance of samples with different binder concentration were given in Table 1. Textile material is an

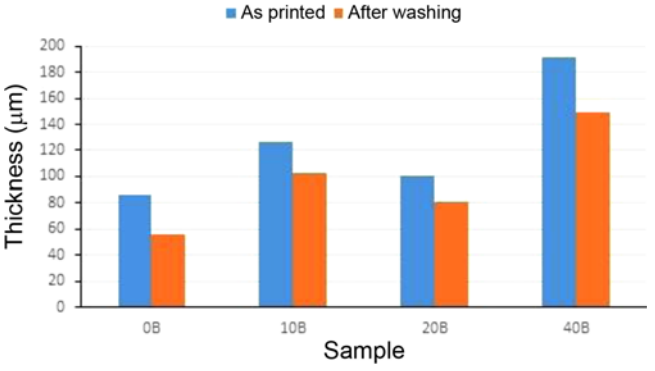

Figure 4. The thickness of the printed fabrics before and after washing.

Table 1. Sheet resistance values of screen printed samples

	Sheet resistance (Ω/sq)	
	As-printed	After washing
PES	1.97E+09	2.28E+09
0B	4.96E+02	4.17E+06
10B	6.80E+02	7.22E+02
20B	5.35E+02	7.90E+02
40B	3.40E+02	6.76E+02

insulator. It can be clearly seen that the electrical resistance decreased significantly by using of carbon nanomaterials. The increase in binder concentration did not effect the electrical properties of printed fabrics. It is known that the electrical conductivity is related to the amount of conductive fillers in the printing paste. In this study, the amount of conductive carbon materials was fixed, so the sheet resistance of the printed fabrics did not reveal a marked change. However, after washing process, the sheet resistance of printed fabric without binder (0B) increased significantly. Sheet resistance values of printed fabrics with different binder concentrations increased slightly after washing process. From these results, it can be said that the conductive network is not damaged by the washing process. The presence of binder in the printing paste positively affected the sheet resistance of printed fabrics.

EMSE Results

The effects of binder concentration and washing process on the EMSE of carbon-based screen printed polyester fabric over the frequency ranges of 15-3000 MHz are given in Figure 5 and 6. In Figure 5, the EMSE of the as-printed fabrics is given. As it can be seen, the EMSE of printed fabrics do not have linear correlation with the binder concentration. Because of the polymeric structure of binder, it gives an insulation property to the printing paste. Also, it is important to obtain homogeneous dispersion of carbon black and graphite particles for good EMSE. The highest EMSE values were obtained as 14.30 dB at low frequency range (15 MHz) at the fabric printed with 40 % binder and as 12.36 dB at high frequency range (2190 and 2205 MHz) at the fabric printed with 10 % binder concentration. However, the EMSE of fabric printed with 40 % binder shows a sharp decrease and becomes the second highest EMSE. It can be explained by the phenomenon that the presence of much polymeric material in the printing paste has considerable effect on the EMSE. Furthermore, the reason for the relatively high EMSE can be the increase of the print thickness due to the increase of paste viscosity.

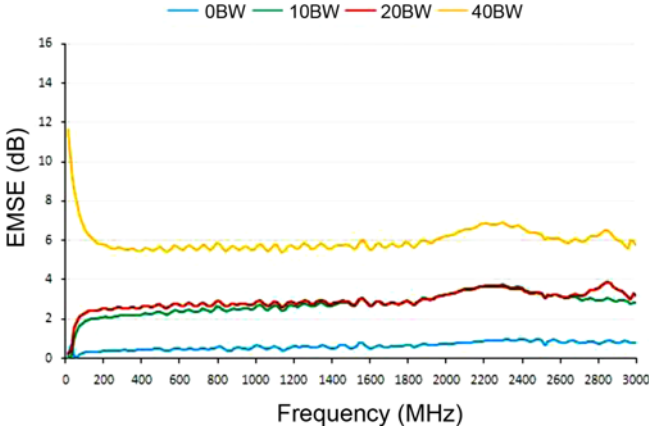

Figure 5. The EMSE of the as-printed fabrics.

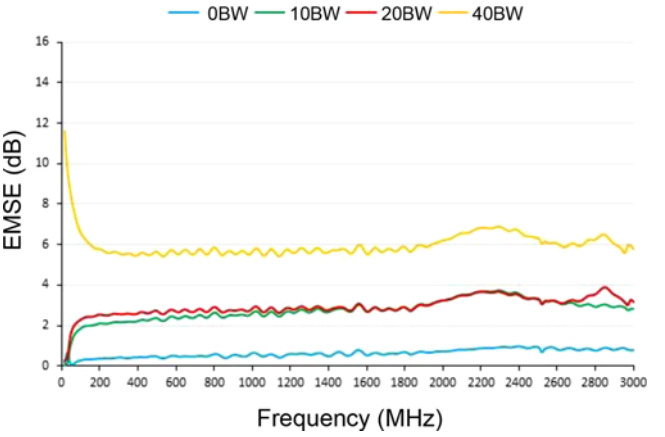

Figure 6. The EMSE of the printed fabrics after washing.

In Figure 6, the effect of binder concentration after washing process on EMSE of carbon-based screen printed polyester fabric over the frequency ranges of 15-3000 MHz is given. It can be clearly seen that all the EMSE of printed fabrics show significant decrease. As expected, the most decrease was seen in fabric printed without binder while the less decrease was seen in fabric printed with 40 % binder. The highest binder concentration keeps the carbon materials within the fabric during washing and avoids the material loss. After washing process, the highest EMSE values were obtained as 11.63 dB at low frequency range (15 MHz) and 6.90 dB at high frequency range (2295 MHz) at the fabric printed with 40 % binder. Besides, the fabrics printed with lower binder concentrations, more significantly 10B, have higher decrease in EMSE values.

SEM Analysis

The characterization of the surface morphology of the fabrics was carried out by scanning electron microscope. The SEM analysis of the PES fabric and as-printed fabrics is given in Figure 7. The pristine PES fabric (Figure 7(a)) shows a well-organized woven structure which consists of very smooth yarn surface. The SEM images clearly demonstrate that the carbon-based screen printing is formed on the surface fabrics and penetrates between the fibers. In Figure 7(b), it can be seen that the carbon-based printing is not uniformly covered the surface of the fabric, it also penetrates between the fibers. The Figures 7(c)-(d) illustrate the thin layer of carbon-based printing is formed on the surface of fabrics. The surface of these printed fabrics has cracked but smoother morphology. However, the most uniform and smoothest surface can be seen with the fabric printed with 40 % binder (Figure 7(e)).

The SEM analysis of the printed fabrics after washing is given in Figure 8. It can be clearly seen from the Figure 8 that the surface of all printed fabrics becomes deformed after

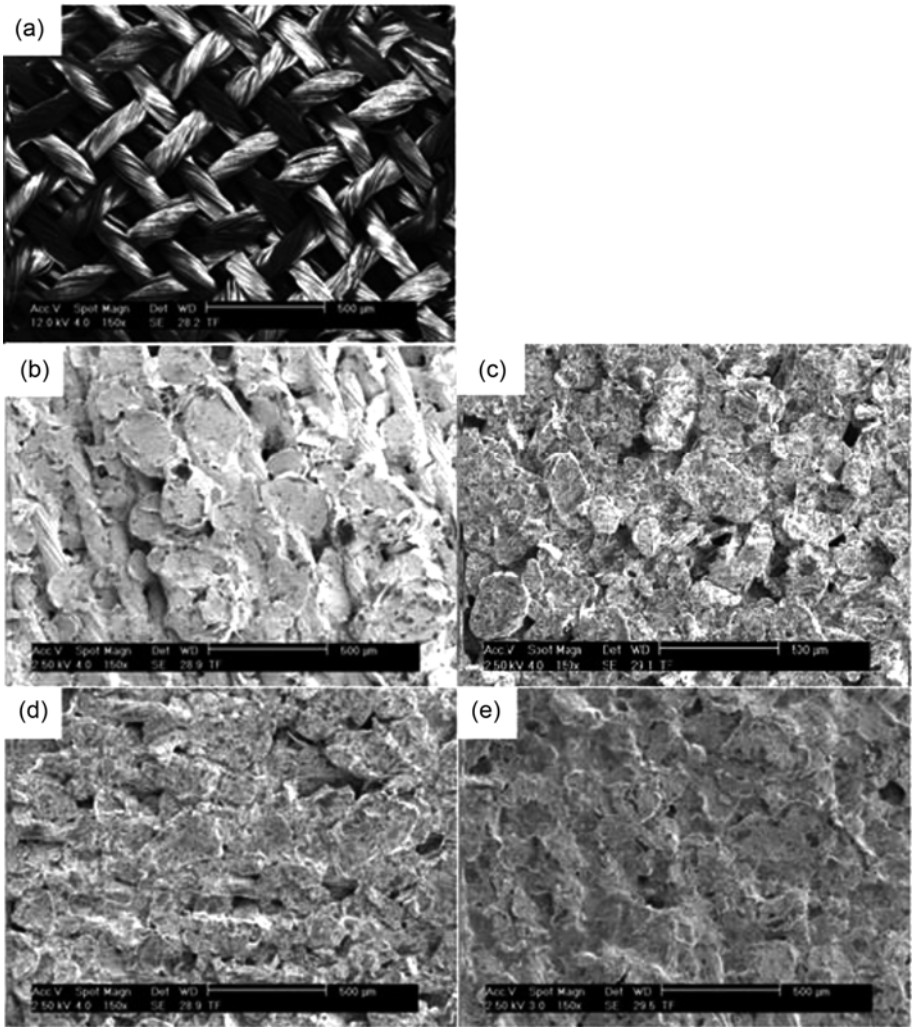

Figure 7. SEM images of the printed fabrics before washing; (a) PES fabric, (b) 0B, (c) 10B, (d) 20B, and (e) 40B.

washing process. From Figure 8(a), it is obvious that the fabric printed without binder has almost nothing on the surface. The carbon-based printing was removed from the surface by washing process. However, the remains from the carbon-based printing penetrated between the fibers can be seen. In Figures 8(b) and (c), the gaps formed on the surface of the fabrics printed with 10 % and 20 % binder, respectively, after washing process can be seen. The less damaged and deformed fabric is the fabric printed with 40 % binder (Figure 8(d)). Furthermore, agreeing with the data obtained from EMSE results of the printed fabrics after washing, the fabric printed with 40 % binder was found to be optimum durable to the washing.

Color Coordinates and Δ*E* Results

The CIE Lab color coordinates of the printed fabrics before and after washing are given in Table 2. The results indicate that the dark colors are obtained compared to the original fabric. It can be seen that increasing the amount of binder caused an increase in L^* value. a^* and b^* values of printed fabrics are both close to zero, indicating that the color values are negligible. From the data obtained after washing process, it can be clearly seen that the washing process has caused an insignificant effect on L^* values of printed fabrics. The darkness of printed fabrics still remains after washing. Moreover, the printed fabric without binder also has no significant change. Also, the L^* value of the fabric printed with 40 % binder remained almost the same compared with the value before washing.

Table 3 shows the color differences between as-printed and washed fabrics. The Δ*E* values clearly showed no visible color difference between the fabrics printed without binder, with 20 % and 40 % binder, which demonstrated washing process did not has a substantial effect on the final color of the fabrics. The Δ*E* value of the fabric printed with 10 % binder has shown the highest color difference,

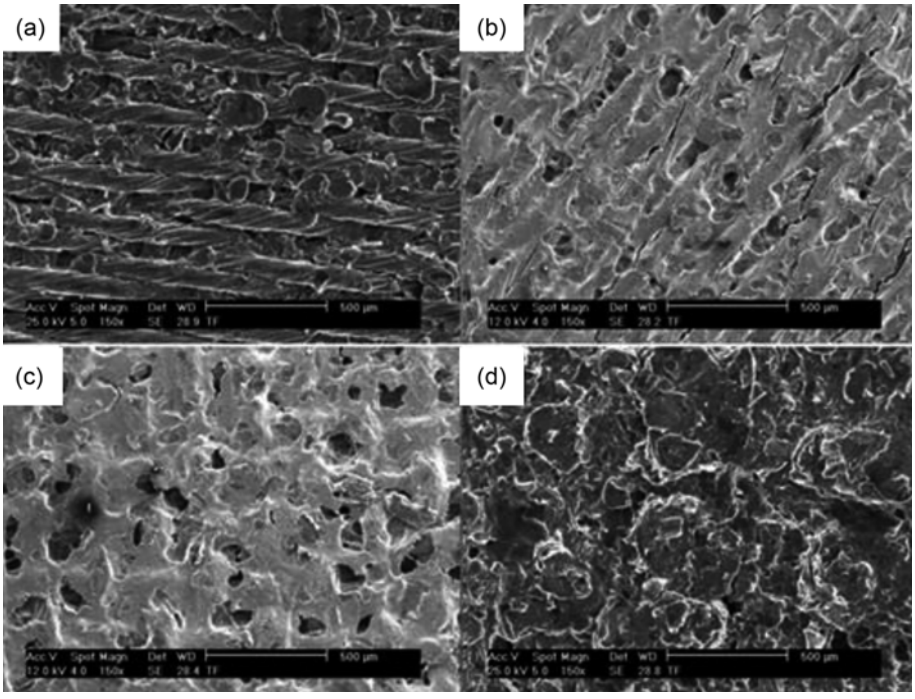

Figure 8. SEM images of the printed fabrics after washing; (a) 0B, (b) 10B, (c) 20B, and (d) 40B.

Table 2. Color coordinates (CIE $L^*a^*b^*$) of the printed fabrics before and after washing

Sample	L^*	a^*	b^*	C	h	X	Y	Z
0B	20.15	0.17	0.56	0.59	73.44	2.88	3.03	3.16
10B	20.98	0.14	0.32	0.35	66.15	3.08	3.24	3.43
20B	26.09	0.42	0.69	0.81	58.65	4.56	4.78	4.98
40B	24.62	0.3	0.5	0.59	58.93	4.09	4.29	4.51
				After washing				
0BW	21.53	0.38	0.18	0.42	25.19	3.23	3.39	3.6
10BW	28.81	0.57	0.46	0.73	39.07	5.51	5.76	6.08
20BW	27.47	0.54	0.42	0.69	37.97	5.03	5.26	5.55
40BW	24.75	0.43	0.44	0.61	45.97	4.14	4.33	4.57

Table 3. Color differences of the printed fabrics

		ΔE
0B	0BW	1.44
10B	10BW	7.838
20B	20BW	1.413
40B	40BW	0.192

meaning that the carbon-based printing on the surface of the fabric has become damaged and deformed. The ΔE value closest to zero was obtained at the fabric printed with 40 % binder. The data obtained from the color coordinates and SEM images simultaneously showed the fabric printed with 40 % binder is more durable than the others.

Staining and Washing Fastness Results

The staining and washing fastness properties of the carbon-based printed fabrics are given in Table 4. The staining results indicate that the fabrics printed without binder and with 10 % binder have values closer to the best. However, the fabrics printed with 20 and 40 % binder have the best results, indicating that there are no staining. The washing fastness results for all printed fabrics have the best, meaning that no visual changes were observed between the as-printed and washed fabrics.

Conclusion

In this paper, for the first time, the effect of binder concentration on the electromagnetic shielding efficiency

Table 4. Staining and Washing Fastness properties of the printed fabrics

Sample	Staining						Washing fastness
	Wool	Acrylic	Polyester	Polyamide	Cotton	Acetate	
0B	4/5	4/5	4/5	4/5	3/4	4/5	4/5
10B	4/5	4/5	4/5	4/5	4/5	5	5
20B	5	5	5	5	5	5	5
40B	5	5	5	5	5	5	5

property of carbon-based screen printed polyester fabric was investigated. The sheet resistance results revealed that the binder has a positive effect. After washing process, the sheet resistance of printed fabrics almost remains the same. The highest sheet resistance after washing was obtained at high binder concentration. The EMSE was measured in the frequency range from 15 to 3000 MHz. The results indicated that the carbon-based screen printed polyester fabric has EMSE of 12.36 dB at 2190 and 2205 MHz at low binder concentration. After washing process, the EMSE of printed fabrics decreased and the screen printed fabric with the highest binder concentration has the EMSE of 6.90 dB at 2295 MHz. This result suggests that the highest binder concentration avoids the material loss during washing process. Moreover, the surface morphologies and color difference values of fabrics after washing process also have positive contribution to this result. Washing fastness and staining results have acceptable values and indicate that increased binder concentration has an improving effect.

As a result of the present study, it was suggested that the proposed carbon material based screen printings were a suitable electromagnetic shielding materials with the advantages of light weight, simple manufacturing process and low cost. The carbon based screen printed textiles has potential in the area of conductive and electromagnetic shielding textiles. For the future works, it is suggested to improve the washing durability of the electromagnetic shielding effectiveness and study the mechanical and physical properties.

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