Mustafa Sabri Ozen[1,2], Ismail Usta[1], Metin Yuksek[1], Erhan Sancak[1,2,*], Navneet Soin[2]

Investigation of the Electromagnetic Shielding Effectiveness of Needle Punched Nonwoven Fabrics Produced from Stainless Steel and Carbon Fibres

DOI: 10.5604/01.3001.0010.5636

[1] **Marmara University, Technology Faculty, Department of Textile Engineering,** Istanbul, Turkey
* E-mail: esancak@marmara.edu.tr

[2] **University of Bolton, Institute for Materials Research and Innovation (IMRI),** Bolton, UK

Abstract
The electromagnetic shielding effectiveness (EMSE) of needle punched, nonwoven fabrics produced using staple stainless steel and carbon fibres was investigated. Utilising carding and large scale industrial type needle punching machines, webs of staple stainless steel and carbon fibres were produced, which were subsequently bonded on the needle punching machine at approximately 132 punches/cm^2 and 13.5 mm needle penetration depth. The effect of varying the carbon fibre content was studied by varying the blend ratio of stainless steel and carbon fibres between 5-20%. EMSE measurements of as-produced needle punched nonwoven fabrics were carried out using the coaxial transmission line method (ASTM D4935-10) in the frequency range of 15-3000 MHz. Within the range, the EMSE values were enhanced from 22.3 dB (95/5, stainless steel/carbon) to 44.7 dB (80/20, stainless steel/carbon), which was attributed to the enhanced conductivity of the fabrics. In fact, the surface resistivity of the samples decreased from 5.80E + 3 Ω to 2.43E + 2 Ω, enhanced for 95:5 and 80:20 stainless steel/carbon blends.

Key words: *carbon fibre, electromagnetic shielding, nonwoven, stainless steel fibre, needle punching.*

Introduction

The number of electromagnetic electronic devices and amount of equipment, ranging from televisions to mobile phones and wireless communication systems, have dramatically increased all over the world. While it is of little doubt that these advances have enhanced the standard of living for people worldwide, nevertheless these devices emit electromagnetic radiation. Electromagnetic radiation, particularly at high frequency, tends to interfere with electronics and for proper operation requires shielding. Moreover it has been established that long term exposure to acute electromagnetic radiation can have harmful effects on human tissue and can interfere with certain bio-electronic devices such as pacemakers [1, 2]. Electromagnetic shielding materials are thus necessary to protect human health and electronic devices against the harmful effects of these electromagnetic waves.

Metals are usually considered to be the best electromagnetic shielding materials for reflecting electromagnetic waves owing to their high conductivity and permeability. However, metals are bulky, expensive, and difficult to process, and suffer from oxidation and corrosion problems associated with exposure to an ambient environment. In contrast, the light weight and anti-corrosive properties of conductive polymer materials are extremely suitable for electromagnetic shielding [3]. Conductive polymers such as polyaniline, polypyrrole and polythiophene are usually deposited on a textile or nonwoven fabric surface for shielding applications. Methods such as the vacuum deposition of metals (metallization) on textile materials such as nylon, polyester and polyurethane have also been discussed in the literature [2, 4]. However, both these methods significantly deteriorate the fabric drape and garment comfort. Similarly, to add suitable conductivity to thermoplastic intrinsically nonconducting polymers, conductive nanomaterials of copper, carbon black, graphene, carbon fibres and carbon nanotubes have also been utilised [5]. In fact, electromagnetic interference shielding is a rapidly growing application of carbon materials, especially staple carbon fibres, owing to their superior properties of high electrically conductivity, high tensile strength, high thermal conductivity & fire resistance and ease of processing. As described in the literature, high EMSE performance from short carbon fibre based materials is expected owing to their high electrical conductivity. In a topical review carried out by Chung et al, it was established that as the amount of carbon fibre in the material increases, the EMSE of the material increases. Electromagnetic shielding materials made from continuous filament fibres have higher EMSE performance as compared to those prepared using short staple carbon fibres. EMSE performances of materials produced from carbon fibre differ depending on the carbon content. There are many thermoset and thermoplastic composite materials reinforced with carbon fibre for EM applications. Materials made from continuous filament fibres have higher EMSE performance comparing to those produced from short staple carbon fibre [6, 7]. In the literature, carbon fibre based textile structures were processed through routes such as weaving and knitting techniques using steel, silver and carbon fibre, core yarns with metal wire and carbon fabric [2, 8]. However, no studies on the preparation of high EMSE nonwoven textiles utilising staple carbon fibres have been found in the literature.

In the present study, we aim to investigate the electromagnetic shielding effectiveness of stainless steel, carbon fibre needle punched nonwoven fabrics produced at different blend ratios (5-20 wt% of carbon fibre). In the frequency range of 15-3000 MHz, 95/5, 90/10 and 80/20 blends of stainless staple steel/carbon fibres showed EMSE values of 22.3dB, 35.4dB and 44.7dB, respectively. The results observed were further corroborated using electrical resistivity measurements and ANOVA statistical analysis. The needle punched nonwoven materials developed can find applications in RF shielding and at the lower end of microwave waves used for terrestrial wireless communication, where they shield up to 99% of incident electromagnetic waves.

Experimental study

Materials

For the experimental study, Bekaert Bekinox® stainless steel fibres were procured from Bekaert Ltd. (Belgium). These stainless steel fibres consist of electrically conductive stainless steel fibres as the core and the sheath of wound polyester fibres (50/50 by weight, see the thermos-gravimetric analysis in ***Figure 1***) with a staple length of about 90 mm. Carbon fibres produced from polyacrylonitrile (PAN) were provided by DowAksa Ltd. (Turkey). The continuous carbon fibre filaments were converted to staple fibres by cutting them to a similar staple length as the steel fibres. The physico-mechanical properties for both staple fibres are provided in ***Table 1***. The tensile strength of the stainless steel fibres and carbon fibres were established on an Instron4411 device (UK) based on the TS EN ISO 5079 standard. The device was adjusted to a 10 mm/min test speed and 10 mm gauge length for testing. The stainless steel fibres were used for increasing the conductive ratio in the needle punched nonwoven fabric. The role of steel fibres in EMSE is to increase the EMSE value of nonwoven fabrics.

Thermo-gravimetric analysis (TGA) was carried out to determine the amount of polyester sheath in the stainless steel fibre core. The TGA analysis was performed on a TA Instruments SDT 2960 DTA-TGA (USA) in the range of 20-700 °C at a heating rate of 10 °C /min under dry air flow. The TGA analysis showed that the residual weight of the stainless steel fibres was 49.30%, which corresponds well with the data provided by the manufacturer [9]. The TG curve and corresponding derivative curve (DTG) of the stainless steel fibre are given at ***Figure 1***. It was understood that the decomposition of the polyester component of the stainless steel fibre occurs in the range of 365-453 °C, with two DTG peaks at 412 °C and 448 °C. In ***Figure 1***, the combustion of the polymer component produced enough energy that the temperature momentarily increased more than the programmed rate, which accounts for the unusual shape of the curve, due to the cooling that followed the reactive overheating.

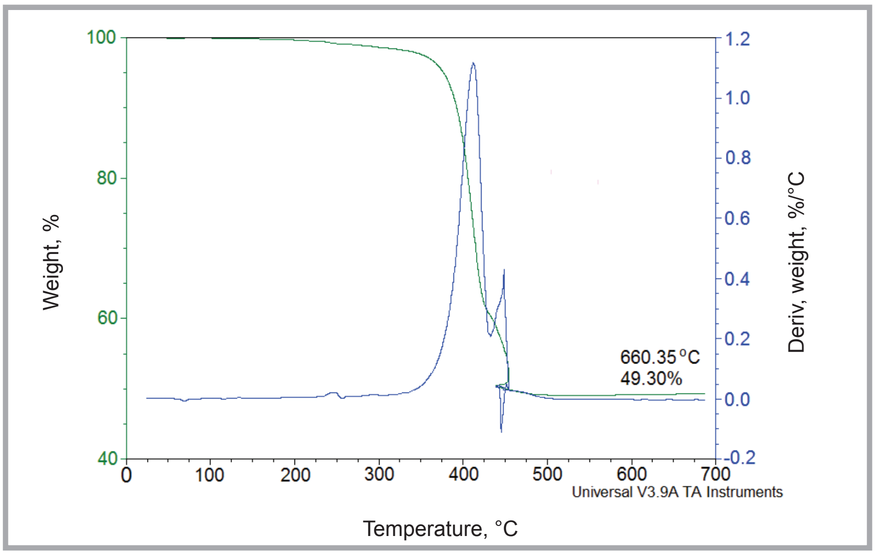

Figure 1. *TGA analysis of stainless steel fibre.*

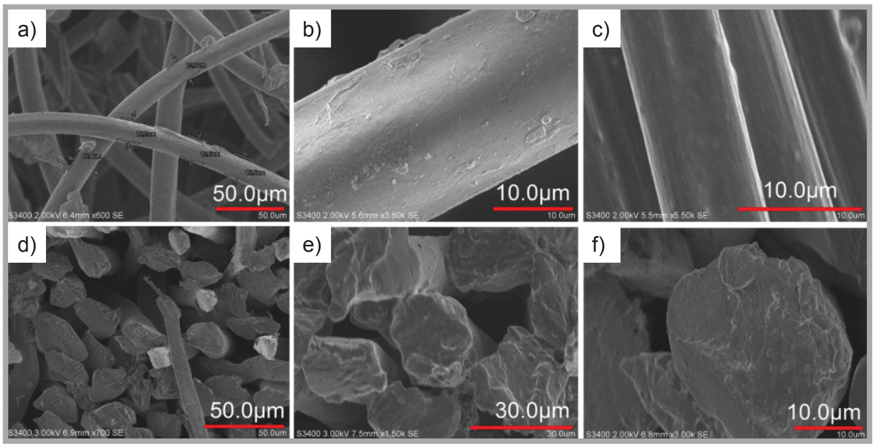

Figure 2. *SEM (a, b) longitudinal images of stainless steel, (c) carbon fibres and (d, e, f) cross-sectional images of stainless steel fibre.*

SEM images of the longitudinal view and cross section of the staple carbon and stainless steel fibres used in the study are shown in ***Figure 2***. These SEM images indicate that both of these fibres have a cross section nearly circular. It was seen that the staple carbon fibre is finer than the stainless steel fibre. Images of the needle punched nonwoven fabrics produced, presented in ***Figure 3***, were taken using microscopy at a magnification of 10x. Processing and analysis of these SEM images was performed with ImageJ software and ImageJ map images from colour differences between the staple carbon and stainless steel fibres were obtained. The ImageJ map images clearly show the increase in the amount of carbon fibres.

Table 1. *Properties of fibres used in experimental study.*

Properties of fibres	12.7dtex stainless steel polyester/steel fibres (Bekaert)		Staple carbon fibre (DowAksa)
	Polyester fibre part	Steel fibres part	
Fineness of fibre, dtex	3.6	9.1	0.66
Staple length of fibre, mm	90		100
Diameter of fibre, μm	–	12	6.45
Breaking load, cN	15.47		14.35
Breaking strength, cN/tex	12.18		217.42
Elongation at break, %	40.43		1.8

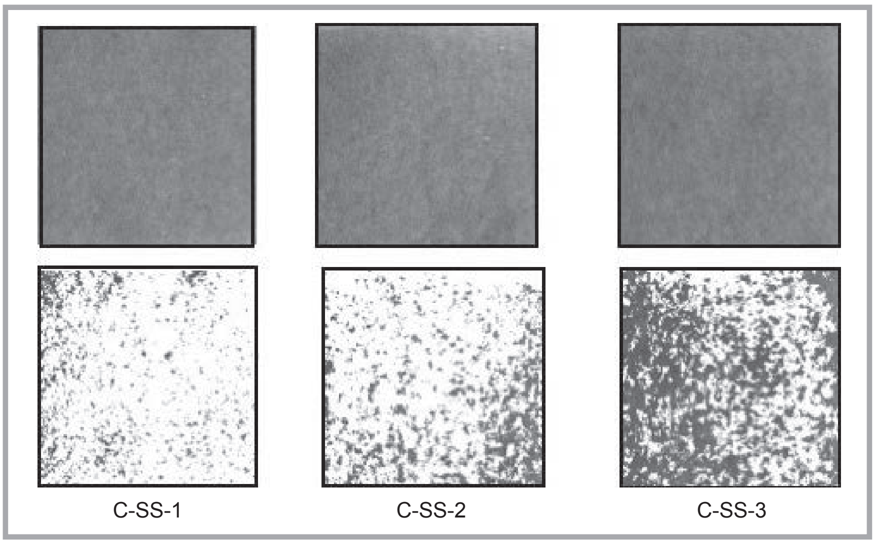

Figure 3. *Needle punched nonwoven fabric samples (taken at x10 magnification).*

Method

The carbon content was chosen as 5%, 10% and 20% by weight, with the samples being mixed according to the weight percentage as shown in ***Table 2***. Carding and needle punching technologies were used for the web formation and subsequent bonding. As the shielding effectiveness depends not only upon the electrical conductivity of the fibre, but also upon its homogeneous distribution, before the carding operation, the staple carbon fibres and stainless steel fibres were opened and blended together. As the fibres used in the experimental study are conductive, no antistatic agent was used. Nonwoven webs were formed with a carding machine from stainless steel fibres and staple carbon fibres. To obtain homogeneous mixing, these fibres were carded twice on the carding machine. A second mixture was made on an industrial type needling machine. In the wool type carding machine used for the first stage, the fibre feeding speed was about 0.75 m/min, the main cylinder speed about 640 m/min, and the doffer cylinder speed (delivery speed) was about 21 m/min. These webs were wound and collected on a rotating drum and were further needled at about 132 punches per cm^2 by a DILO needle punching machine (Germany). Foster 15 x 18 x 40 x 3.5 R333 RBA barbed needles were used on this needle punching machine. As observed in the SEM images ***(Figure 2)***, the diameter of stainless steel fibre is between 15-16 µm. Thus a 36 and 40 working gauge are highly suitable for these 1.5 and 6 denier fibres. During the production, the needle penetration depth was adjusted to 13.5 mm in order to prevent breakage of carbon fibres. The working parameters of the needle punching machine are given in ***Table 3***.

Table 2. *Weight percentage of fibres used in needle punched nonwoven fabrics.*

Nonwoven fabrics	Weight, %			Conductive part, %	Non-conducting part, %	Areal density, g/m^2	Thickness, mm
	Stainless steel fibres		Carbon fibres				
	Polyester part	Steel part					
C-SS-1	47.5	47.5	5	52.5	47.5	256.74	2.47
C-SS-2	45	45	10	55.0	45	274.49	2.37
C-SS-3	40	40	20	60.0	40	244.39	2.38

Table 3. *Working parameters of the needle punching machine.*

Needle punching machine rotation, rpm/min	585
Web feeding speed, m/min	3.3
Fabric delivery speed, m/min	5.1
Depth of needle penetration, mm	13.5
Distance between needle boards, mm	19
Needle punch density per cm^2, punches/cm^2	131.8

Now needle punching technology is based on the mechanical bonding of fibres by interlocking staple fibres using long barbed felting needles. Needle punching parameters such as needle penetration and needle punch density were determined to bond fibres well without causing breaking of the stainless steel and carbon fibres. As compared to standard polymeric fibres, they are more susceptible to damage upon repeated mechanical effects. As metallic fibres exhibit poor recovery from bending and can break away easily, especially when processed at the second and third needling stages, only the pre-needling operation was applied to the web and the needle punch density was kept low (***Table 3***). It is shown in the literature that repeated needling and very high punch densities can result in the breakage of fibres, reducing their EMSE values [2]. The areal density and thicknesses (measured using a James H. Heal thickness tester (UK), according to TS EN ISO 9073-2) of needle punched nonwoven fabrics are listed in ***Table 2***, with the corresponding percentages of conductive and non-conductive parts. It is an established fact that upon increasing the needling density/punch density and depth of needle penetration, the thickness of the resulting fabric is reduced. In our previous studies, it was observed that as the thickness of nonwoven fabric decreases, the electromagnetic shielding effectiveness of nonwoven fabric decreases as well [10]. The types of needle barb are classified according to fibre carrying capacities. Increasing the fibre carrying capacities of barbs also reduces the thickness of nonwoven fabric. This result affects the EMSE of nonwoven fabric [11].

EM shielding effectiveness (EMSE) measurements

Shielding can be specified in the terms of the reduction in the magnetic and electrical field or plane-wave strength caused by shielding. The effectiveness of a shield and its resulting EMI attenuation are dependent on the frequency, the distance of the shield from the source, the thickness of the shield, and the shielding material.

Shielding effectiveness (SE) is normally expressed in decibels (dB) as a function of the logarithmic ratio of the incident and exit electric (E), magnetic (H) or plane-wave field intensities and is defined by SE (dB) = 20 log (E0/E1), SE (dB) = 20 log (H0/H1) and SE (dB) = 20 log (F0/F1), respectively.

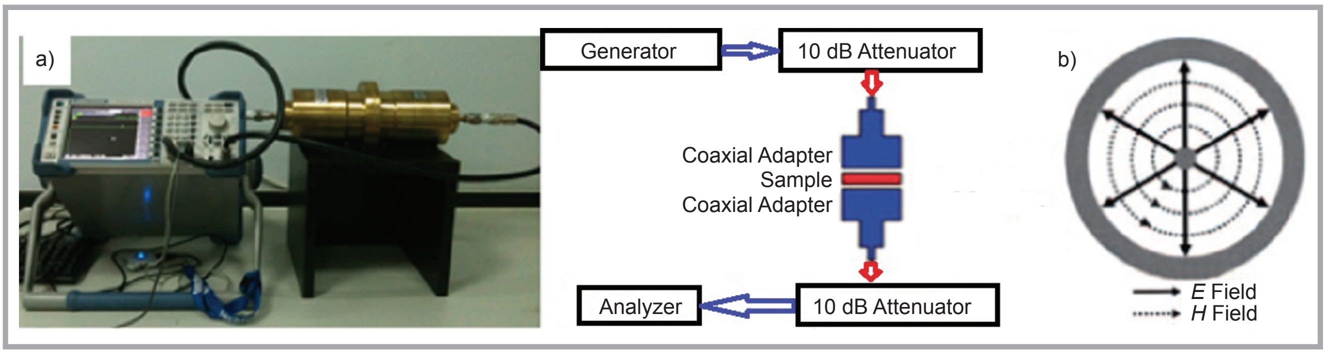

***Figure 4.** a) Set-up with coaxial adapters, b) electric (E) and magnetic (H) field distribution inside a coaxial line [8].*

The electromagnetic shielding effectiveness of the as-produced needle punched nonwoven fabrics were determined using the ASTM D 4935-10 coaxial transmission line standard method for planar materials standard. This standard determined the shielding effectiveness of the textile structures using the insertion-loss method. and is shown in ***Figure 4***. The technique involves irradiating a flat, thin sample of the base material with an EM wave over the frequency range of interest, utilizing a coaxial and a flanged outer conductor [12].

For our analysis, a shielding effectiveness test fixture (Electro-Metrics, Inc., model EM-2107A, USA) was used to hold the sample, with a network analyser generating and receiving EM signals. Test specimens were kept between the two metal coaxial electrodes in contact. A pressure of 45 grams per cm^2 for each needle punched nonwoven fabric was applied during testing. The shielding effectiveness was determined from ***Equation (1)***, which is the ratio of the incident field to that which passes through the material.

$$EMSE = 10\log\left(\frac{P_1}{P_2}\right) \quad (1)$$

Where P_1 (watts) is the power received with the fabric present and P_2 (watts) is that received without the presence of the fabric. The input power used was 0 dB, corresponding to 1 mW. The reflectance (R_e) and transmittance (T_r) of the composite were also measured, and the absorbance (A_b) was calculated using ***Equation (2)*** as follows:

$$A_b = 1 - T_r - R_e \quad (2)$$

Where, R_e and T_r are the square of the ratio of reflected (E_r) and transmitted (E_t) electric fields to the incident electric field (E_i), respectively, obtained from ***Equations (3)*** and ***(4)***.

$$R_e = \left|\frac{E_r}{E_i}\right|^2 = |S_{11}(¿S_{22})| \quad (3)$$

$$T_r = \left|\frac{E_t}{E_i}\right|^2 = |S_{21}(¿S_{12})|^2 \quad (4)$$

R_e and T_r were obtained by measurement of S-parameters, S_{11} (or S_{22}) and S_{12} (or S_{21}) for the reflection and transmission, respectively. The measurement device consists of a network analyser, which is capable of measuring the incident, transmitted and reflected powers, and a sample holder. The shielding effectiveness is determined by comparing the difference in attenuation of a reference sample and the test sample, taking into account the incident and transmitted power. EMSE values of the three different needle punched nonwoven fabrics C-SS-1 (95/5), C-SS-2 (90/10) and C-SS-3 (80/20), as described in ***Figure 5***, were measured in the range of 15-3000MHz, with the results presented being the average of five readings.

Results and discussion

Surface resistivity

The surface resistivity of the needle punched nonwoven fabrics with stainless steel and carbon fibre is shown in ***Figure 5.c***. It was observed that the needle punched nonwoven fabric with 20% staple carbon fibre (C-SS-3) had the lowest surface resistivity (2.43E+02 Ω) as compared to the needle punched nonwoven fabrics containing 10% (1.51E+03 Ω) and 5% (5.83E+03 Ω) carbon fibre. By definition, a lower surface resistivity implies higher conductivity [27, 28] and hence it can be said that the nonwoven fabrics with 20wt.% carbon fibre are more conductive than the other nonwoven fabrics. Conductivity is one of the most significant parameters affecting the EMSE properties of materials. It is well established that materials with higher conductivity tend to show higher EMSE performance [7].

In accordance with the surface resistivity measurements, the EMSE measurements showed a similar trend. ***Figure 5.a*** shows the EMSE values of needle punched nonwoven fabrics produced from stainless steel fibres with staple carbon fibres at different ratios in the 15-3000 MHz frequency range. As the frequency increases, EMSE values of all the needle punched nonwoven fabrics show an almost linear increase. The structures with smaller gaps between conductive fibres display higher overall EMSE shielding effectiveness at high frequency. Moreover bigger gaps between conductive fibres displays a higher overall EMSE shielding effectiveness at low frequency [13-16]. It was clearly seen that as the amount of carbon fibre used in needle punched nonwoven fabrics increases, EMSE values also increase in the 15-3000 MHz frequency ranges. The C-SS-3 nonwoven fabric with 20% carbon fibre obtained the highest 44.7 dB EMSE value in the 3000 MHz frequency range, while the C-SS-2 and C-SS-1 samples showed 35.4 dB and 22.3 dB, respectively, in the same frequency range. These values are significantly higher than the control sample of pristine stainless steel needle punched nonwoven fabric. These values are similar to those observed by Kim and Chung, who investigated properties of the electromagnetic shielding effectiveness of carbon fibre nonwoven mat, nickel coated carbon fibre nonwoven mat, filament carbon fibre woven fabric and nickel/copper coated polyester knitted fabric. In their study, the highest shielding effectiveness of 53 dB at 1.0G Hz was attained by the metal-coated polyester knitted fabric. It was found that nonwoven fabric with nickel coated carbon fibre was superior in shielding compared to bare carbon fibre nonwoven mat [17]. Similarly, Ting-Ting L. et.al developed a composite structure

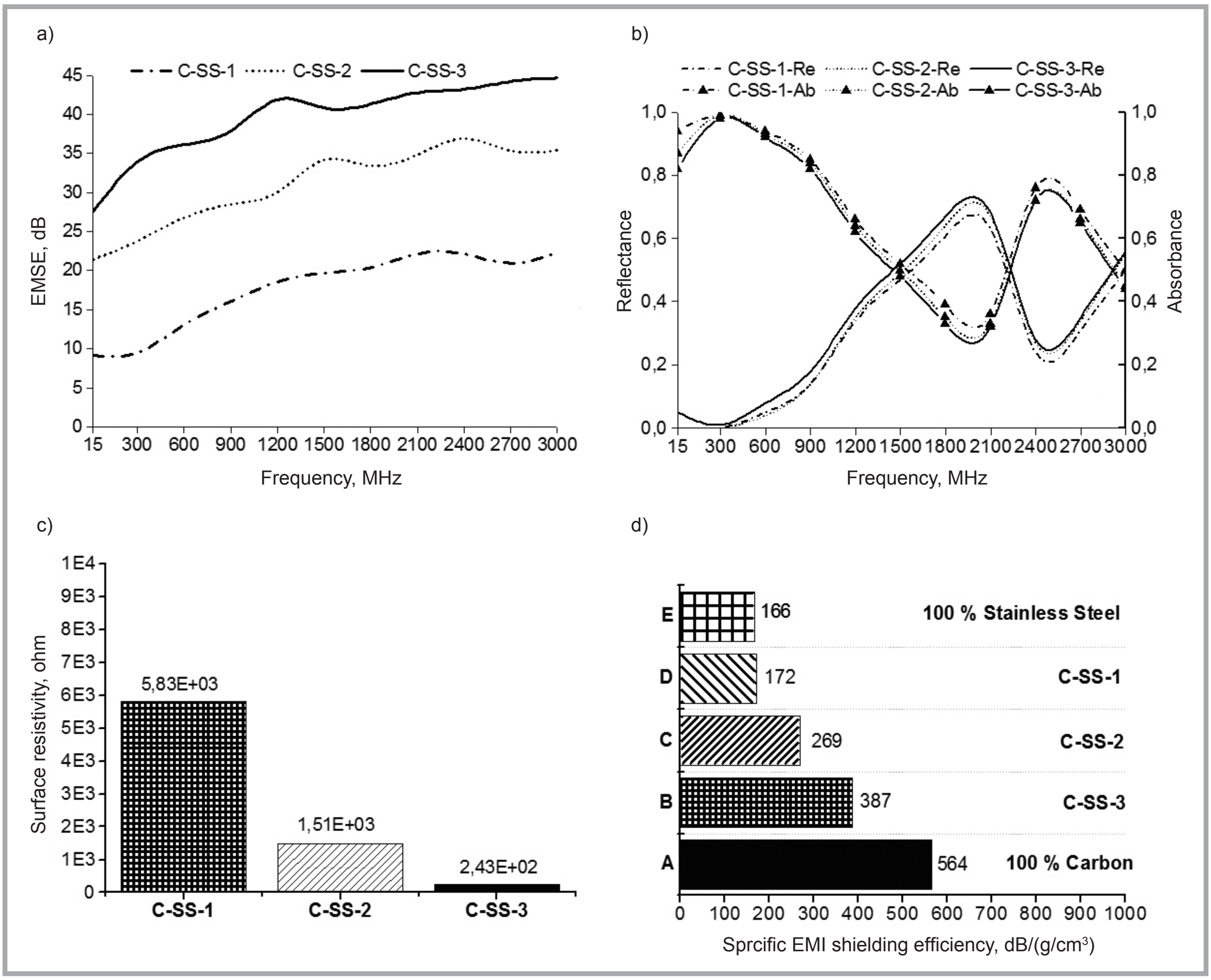

Figure 5. *(a) EMI shielding efficiency of needle punched nonwoven fabrics with different percentages of carbon fibres between 15 MHz and 3000 MHz, (b) absorbance and reflectance results of needle punched nonwoven fabrics with different percentages of carbon fibres between 15 MHz and 3000 MHz, (c) surface resistivity results for needle punched nonwoven fabrics, (d) comparison of specific EMI shielding efficiency of our data with other results reported.*

with three layers consisting of carbon woven fabric and needle punched nonwoven fabrics for a wall interlayer and package interline applications. Nonwoven fabrics consisting of staple Kevlar fibres, melt staple polyester, nylon6 staple fibres and carbon woven fabrics were combined using a pre-needle punching machine and the structure further bonded with a calendaring machine at 160 °C. It was found that hot-pressed composites with three layers reached an optimal electromagnetic shielding effectiveness of 65 dB in a very high frequency range between 2000-3000 MHz [18]. However, with multiple steps, the processing of the material is much more time consuming, unlike our samples. From this experimental study, it was understood that staple carbon fibres had a considerable effect on electromagnetic shielding effectiveness results.

Morari et.al studied the electrical conductivity and electromagnetic shielding effectiveness of composite materials made from silicone rubber with carbon and ferrite powder in microwave and terahertz frequency ranges [19]. Chang et.al studied the electromagnetic shielding of waterborne polyurethane composite film added carbon fibre, nickel nanoparticles and multiwalled carbon nanotubes by the polymer blending method. At 1000 MHz frequency, the shielding effectiveness of conductive composite film prepared with carbon fibre/nickel nanoparticles reached 28 dB. At loadings of 33wt% carbon fibre in conjunction with 13wt% carbon nanotubes, the shielding effectiveness reached 33.7 dB at 1000MHz [20]. Huang et.al investigated the electromagnetic shielding effectiveness of cement based composites filled with carbon black and carbon fibre. The shielding effectiveness gradually improved with an increase in carbon fibre content and attained a maximum of 21 dB at 1.5 GHz. It was emphasised that carbon fibre is a much more effective additive than carbon black for EMI shielding [21]. As mentioned earlier, most of the existing studies focus on composite structures, knitted or woven fabrics coated with conductive polymers such as polypyrolle, polyaniline or conductive powders, composites and fabrics produced with conductive core yarn. There is a significant lack of literature on the electromagnetic shielding properties of nonwoven fabrics produced directly from conductive fibres.

Figure 5.b shows the absorbance and reflectance values measured from the needle punched nonwoven fabric samples in the 15-3000 MHz frequency range. All

the nonwoven samples show decreased reflectance and increased absorbance of electromagnetic waves with increasing frequency [22-25]. According to Chung, the primary mechanism of EMI shielding is usually reflection, which requires mobile charge carriers, such as electrons, which interact with the electromagnetic fields in radiation. Similarly a secondary mechanism of EMI shielding is associated with absorption which occurs when the EM shield has electric/magnetic dipoles, which can interact with the electromagnetic fields in the radiation [7]. Both the reflection and absorption of electromagnetic waves are related to the properties of conductive fillers. For our samples, the absorption values decrease as a function of the frequency in the range of 15-2000 MHz with a corresponding increase in the reflectance values. This behaviour is expected considering the absorption values for stainless steel and carbon fibres are much higher than the reflectance of electromagnetic waves. ***Figures 5.a***, ***5.b*** shows the values of absorbance, reflectance and EMI shielding at frequencies 15-3000 MHz. Three measurements from each nonwoven fabric sample were made.

Figure 5.d shows the density specific EMSE of nonwoven fabrics in comparison with values reported by other researchers [10]. Nonwoven fabric (E) with stainless steel fibre was compared with nonwoven fabrics (B, C, D) with steel fibre and carbon fibre, and multi-axial fabric (A) with 100% carbon fibre. It can be seen that the nonwoven fabrics with stainless steel and carbon fibres have higher specific EMI SE than the nonwoven fabric with 100% stainless steel fibre, and lower specific EMI SE than the multi-axial fabric with 100% carbon fibre, possibly resulting from material properties. It is known that the stainless steel fibre consists of 50/50% polyester and steel fibre. As it is not possible to produce a needle punched nonwoven fabric from carbon fibres without crimp by carding and needle punching technology, the nonwoven fabrics were compared with multi axial fabric (A) consisting of 100% carbon filament fibres.

In order to ascertain and demonstrate the effect of carbon fibre on the EMSE values of stainless steel-carbon fibre samples, one-way ANOVA analysis with SPSS 13.0 was carried out and the statistical results evaluated at a 5% significance level. The analysis clearly shows the effect of increasing the percentage of carbon fibre on the EMSE of needle punched nonwoven fabrics. Through analysis, three groups of nonwoven fabrics with different carbon rates are identified (Group I: % 5 C, Group II: %10 C, Group III: %20 C). The results in ***Table 4*** show that there is a significant difference across the groups in terms of the mean value of EMSE. Besides this, a post hoc test – the Tukey test, for multiple comparisons – was used to determine which of these groups differ from each other. Accordingly each fabric with a different carbon rate varied from the others in a significant way ($p<05$). The needle punched nonwoven fabrics with a 20%, 10% and 5% blend of staple carbon fibre obtained average EMSE values of 39.49 dB, 30.98 dB and 17.67 dB, respectively. As a result, it is found that EMSE increases with the increasing of percentage of carbon fibre in needle punched nonwoven fabrics.

EM shielding textiles have two classes: professional and general use. ***Table 4*** shows the performance specifications of EM shielding textiles both in general use and professional use. While EM shielding textiles in general use achieve shielding up to a level of 30 dB, professional use products achieve shielding from at least 30 dB up to 50 dB and higher. Casual wear, uniforms (computer and Telecom Company), aprons, maternity dress and protective covers for consumer electronic products are considered and evaluated as EM shielding textiles in general use. While medical devices, safety uniforms, shielding material for electronic components, assembly equipment and other applications are accepted and evaluated as EM shielding textiles in professional use [26].

Table 4. *Performance specifications of electromagnetic shielding textiles in general and professional use [26].*

Grade	5 Excellent	4 Very good	3 Good	2 Moderate	1 Fair
Percentage of electromagnetic shielding (ES)	SE>99.9%	99.9%≥SE>99%	99%≥SE>90%	90%≥SE>80%	80%≥SE>70%
Shielding effectiveness (SE) in general use	SE>30dB	30dB≥SE>20dB	20dB≥SE>10dB	10dB≥SE>7dB	7dB≥SE>5dB
Shielding effectiveness (SE) in professional use	SE>60dB	60dB≥SE>50dB	50dB≥SE>40dB	40dB≥SE>30dB	30dB≥SE>20dB

Table 5. *One-way ANOVA model for EMSE.* ***Note:*** *Significance level (2-tailed): p<.05; Group I: C-SS-1 (%5C); Group II: C-SS-2 (%10C); Group 3: C-SS-3 (%20C); EMSE: electromagnetic shielding effectiveness, N: the number of measurement, df: degree of freedom, Sig: significant, Std: standardized.*

Dependent variable	Nonwoven fabrics containing different ratios of carbon fibre												F test statistics		
	N			Mean			Std. deviation			Std. error					
	(I)	(II)	(III)	(I)	(II)	(III)	(I)	(II)	(III)	(I)	(II)	(III)	F	df1;2	Sig.
EMSE	11	11	11	17.67	30.98	39.49	4.97	5.23	5.21	1.50	1.58	1.57	50.399	2;30	.000

Multiple comparisons (Tukey HSD)

EMSE		Mean difference	Std. error	Sig.
(I)	(II)	-13.31*	2.19	.00
	(III)	-21.82*	2.19	.00
(II)	(I)	13.31*	2.19	.00
	(III)	-8.51*	2.19	.00
(III)	(I)	21.82*	2.19	.00
	(II)	8.51*	2.19	.00

Conslusions

In this study, the electromagnetic shielding effectiveness of needle punched nonwoven fabrics produced from staple carbon and stainless steel fibres with carding and needle punching technologies was investigated. Firstly, the staple carbon fibres were mixed with the staple stainless steel fibres at 5%, 10% and 20% blend ratios. It was observed that on increasing the carbon fibre ratio in the needle punched nonwoven fabrics, a significant increase in electromagnetic shielding effectiveness can be observed. In fact, the needle punched nonwoven fabric with 20/80% carbon/steel fibre content displays the highest EMSE of 44.7 dB in the 3000 MHz frequency range as compared to 35.4 dB and 22.3 dB for a 10/90% and 5/95% carbon/steel fibre content, respectively. Further analysis of the EMSE behaviour showed that the absorbance and reflectance behaviours of all needle punched nonwoven fabrics are similar to each other in the 15 MHz and 3000MHz frequency range. The enhanced EMSE behaviour was attributed to a significant reduction in the surface resistivity from $5.83E + 03\ \Omega$ for a 5/95% carbon/stainless steel blend to $2.43 + E02\ \Omega$ for a 20/80% carbon/stainless steel blend, which was further confirmed through one-way ANOVA analysis. The high EMSE needle punched nonwoven fabrics developed from stainless steel and carbon fibres have potential application in defence such as in military tents, military secret rooms, protective covers, missile covers and buildings as an EMI shielding material.

Acknowledgements

This study was supported by TUBITAK (The Scientific and Technological Research Council of TURKEY). I would like to thank BEKAERT and AKSACA for the research materials, the Hassan Group for nonwoven fabric production and the University of Bolton, United Kingdom, and the University of Marmara in Istanbul/TURKEY for their contribution to the research work.

Funding

This work was supported by the Scientific Research Project Unit (BAPKO) of Marmara University (project number FEN-E-120314-0067).

References

1. Zamanian A, Hardiman C. Electromagnetic Radiation and Human Health: A Review of Sources and Effects. *High Freq. Electr.* 2005; 16-26.
2. Subhankar M, Kunal S, Pulak D, Mrinal S. Textiles in Electromagnetic Radiation Protection. *J. of Saf. Eng.* 2013; 2(2): 11-19.
3. Safarova V, Militky J. Development of a Hybrid Electromagnetic Shielding Fabric. *18th International Conference on Composite Materials* 2011; 21-26.
4. Avloni J, Lau R, Ouyang M, Florio L, Henn AR, Sparavigna A. Polypyrolle Coated Nonwovens for Electromagnetic Shielding. *J. of Indust. Text.* 2008; 38, 1: 55-68.
5. Chang H, Yeh YM, Huang KD. Electromagnetic Shielding by Composite Films Prepared with Carbon Fiber, Ni Nanoparticules, and Multi-Walled Carbon Nanotubes in Polyurethane. Mater. Transact. 2010; 51(6): 1145-1149.
6. Jana PB, Mallick AK, De SK. Electromagnetic Interference Shielding Effectiveness of Short Carbon Fibre-Filled Polychloroprene Vulcanized by Barium Ferrite. *J. Mater. Sci.*, 1993; 28: 2097-2104.
7. Chung DDL. Electromagnetic interference shielding effectiveness of carbon materials. *Carbon* 2001; *39:* 279-285.
8. Ozen MS, Sancak E, Beyit A, Usta I, Akalin M. Investigation of Electromagnetic Shielding Properties of Needle Punched Nonwoven Fabrics with Stainless Steel Fibres. *Text. Res. J.* 2013; 83(8): 849-858.
9. Varga K, Noisternig MF, Griesser UJ, Alja L, Koch T. Thermal and Sorption Study of Flame Resistant Fibers. *Lenzinger Berichte* 2011; 89P: 50-59.
10. Ozen MS, Sancak E, Akalin M. The Effect of Needle-Punched Nonwoven Fabric Thickness on Electromagnetic Shielding Effectiveness. Text. Res. J.
11. Perumalraj R, Dasaradan BS. Electromagnetic Shielding Effectiveness of Copper Core Yarn Knitted Fabrics. *Indian Journal of Fibre &Textile Research* 2009; 34: 149-154.
12. ASTM D4935-10:2010. Standard Test Method for Measuring the Electromagnetic Shielding Effectiveness of Planar Materials.
13. Ortlek H G, Gunesoglu C, Okyay G, Turkoglu Y. Investigation Of Electromagnetic Shielding And Comfort Properties Of Single Jersey Fabrics Knitted From Hybrid Yarns Containing Metal Wire. *Tekstil ve Konfeksiyon*, 2012; 22(2): 90-101.
14. Perumalraj R, Dasaradan BS, Anbarasu R, Arokiaraj P, Harish LS. Electromagnetic shielding effectiveness of copper core-woven fabrics. *Journal of the Textile Institute*, 2009; 100(6): 512-524.
15. Cheng KB. Electromagnetic shielding effectiveness of the twill copper woven fabrics. *Journal of Reinforced Plastics and Composites* 2006; 25(7): 699-709.
16. Roh JS, Chi YS, Kang TJ, Nam SW. Electromagnetic Shielding Effectiveness of Multifunctional Metal Composite Fabrics. *Textile Research Journal* 2008; 78(9): 825-835.
17. Kim T, Chung DDL. Mats and Fabrics for Electromagnetic Interference Shielding. *Journal of Materials Engineering and Performance* 2006; 15(3): 295-298.
18. Ting-Ting L, Rui W, Ching-Wen L, Mei-Chen L, Jia-Horng L. Manufacture and Effectiveness Evaluations of High-Modulus Electromagnetic Interference Shielding/Puncture Resisting Composites. *Textile Research Journal* 2013; 83(17): 1796-1807.
19. Morari C, Balan I, Pintea J, Chitanu E, Iordache I. Electrical Conductivity and Electromagnetic Shielding Effectiveness of Silicone Rubber Filled with Ferrite and Graphite Powders. *Progress in Electromagnetic Research M*. 2011; 21: 93-104.
20. Chang H, Yeh YM, Huang KD. Electromagnetic Shielding by Composite Films Prepared with Carbon Fiber, Ni Nanoparticles, and Multi-Walled Carbon Nanotubes in Polyurethane. *Materials Transactions* 2010; 51, 6: 1145-1149.
21. Huang SW, Guang HC, Qi L, Yu HX. Electromagnetic Shielding Effectiveness of Carbon Black and Carbon Fibre Cement Based Materials. *Advanced Materials Research* 2010;168-170: 1438-1442.
22. Kang GH, Kim S H. Electromagnetic Wave Shielding Effectiveness Based on Carbon Microcoil-Polyurethane Composites. *Journal of Nanomaterials* 2014; 1-6.
23. Rea S, Linton D, Orr E, Connell J. Electromagnetic Shielding Properties of Carbon Fibre Composites in Avionic Systems. *Microwave Review* 2005; 29-32.
24. Wu Y, Zhous S, Xu Z, Yu W. Effect of Carbon Fiber Buckling Waved Arrangement on the Absorption of Electromagnetic Wave. Paper presented at the *Asia Pacific Conference on Environmental Science and Technology Advances in Biomedical Engineering*, 2012.
25. LI K, Wang C, Li H, Jiao G, Wei J. Study on the Electromagnetic Interference of CFRC Composites by Reflectivity. *Journal Material Science Technology* 2008; 24: 265-271.
26. FTTS-FA-003: Test Method of Specified Requirements of Electromagnetic Shielding Textiles. Committee for Conformity Assessment on Accreditation and Certification of Functional and Technical Textiles, Taiwan 2003; 1-4
27. Yildiz Z, Usta I, Gungor A. Investigation of the Electrical Properties and Electromagnetic Shielding Effectiveness of Polypyrrole Coated Cotton Yarns. *FIBERS & TEXTILES in Eastern Europe* 2013; 21(98): 32-37.
28. Kaynak A, Wang L, Hurren C, Wang X. Characterization of conductive polypyrole coated wool yarns. *Fibers and Polymers* 2002; 3(1): 24-30.

Received 02.03.2017 Reviewed 02.11.2017