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Functional Properties and Electromagnetic Shielding Behaviour of Elastic Warp-knitted Fabrics

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Abstract

An investigation was made on the electromagnetic shielding behaviour and other functional properties for manufactured multifunctional elastic warp-knitted fabrics. Bamboo charcoal polyester/Crisscross-section polyester (BC-PET/CSP) blended yarns were used as the back of the warp-knitted fabric while conductive composite yarns were used as the front. The variation in the far infrared emissivity and anion density of elastic-warp knitted fabrics produced with different proportions of BC-PET content were studied in detail. Moreover the electromagnetic shielding effectiveness (EMSE) of the fabrics with different elongation was measured in this study. The experimental results showed that increased elongation almost did not significantly affect the EM shielding behaviour of fabric K1 in the elongation range of 0 - 40%. Finally to increase the EMSE of the fabric, the lamination method was used in this study. EMSE measurement results showed that two layer K1 warp-knitted fabrics with 90° interval displayed a better shielding effect against the EM wave compared to that with a 0° interval.

Key words: *functional properties, electromagnetic shielding effectiveness, protective clothing, elastic warp-knitted fabric, electromagnetic wave.*

Introduction

With extensive usage of electrical and electronic devices in our daily life, the harm of electromagnetic (EM) radiation to the human has aroused wide concern among researchers [1, 2]. There is a growing body of scientific evidence that links exposure to electromagnetic waves with a range of negative effects on our health [3]. It has been compellingly linked to serious health problems such as leukemia, brain tumors, Alzheimer's disease, sleeping problems, and depression. Thus to avoid electromagnetic inference (EMI) and protect people from being harmed, protective clothing has been used against electromagnetic wave radiation.

Traditionally metal and alloys are considered to be the best materials for electromagnetic shielding purpose, but they are expensive, heavy and not flexible [4, 5]. On the other hand, the usage of textile for protective clothing has been widely used for their lightweight, flexible, less expensive, and thermal expansion suitability. Unfortunately most textile products are electrically insulating and transparent to EM waves i.e., their inherent electromagnetic shielding effectiveness (EMSE) is practically zeroed [6]. To obtain electrically conductive textiles, two methods are mainly used as protective clothing. The first is the surface treatment of textile such as the lamination of conductive layers onto the surface of textiles, conductive coating, ionic plating, etc. Another method is using fillers such as adding or incorporating conductive composite yarns, fibers and fillers into nonconductive textiles. Surface treatment is not only time-consuming and costly but also the layers deposited have very poor adhesion and wearing comfort [7, 8]. In comparison with traditional surface treatment techniques, using metal filaments to produce conductive metal composite yarns and their textiles has many advantages in terms of flexibility, wearing comfort and scratch resistance properties, etc. [9, 10]. At present, many kinds of conductive fabrics have been developed and used as protective clothing against electromagnetic waves or electrostatic discharge (ESD). However, the functionality of these protective textiles is limited and difficult to meet special requirements such as healthcare, antibacterial, elasticity recover properties, etc. When EM protective clothing is used in sports activity or in our daily life, elasticity is very important because it will not provide comfort but also offer least resistivity during garment stretch.

In this study, the basic aim of our research was to fabricate a type of multifunctional elastic warp-knitted fabric. The study included evaluating the far infrared emissivity, anion releasing density and EMSE of elastic-warp knitted fabrics produced with different proportions of BC-PET content. In this study, rubber thread was used to provide elasticity in the wrap direction for the warp-knitted fabric produced.

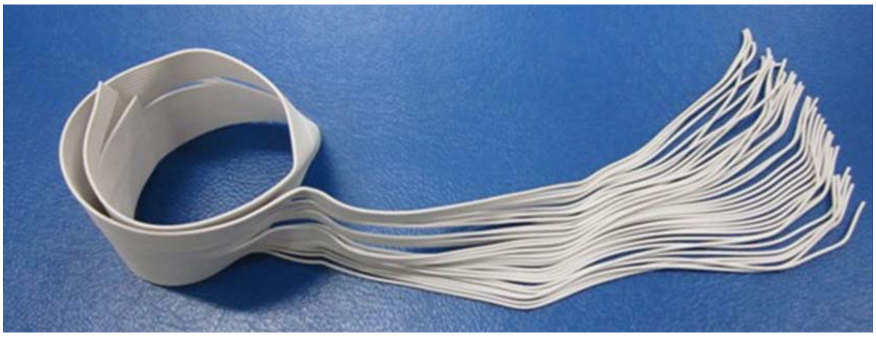

Figure 1. Picture of rubber thread used to produce warp-knitted fabric.

Materials and method

The metal composite yarns used in the construction of warp-knitted fabrics were produced with stainless steel wire (SSW), 150d/144f antibacterial nylon (AN), and 75d/48f crisscross-section polyester (CSP) filaments. With a SSW as the core, the AN filament covered the SSW in the Z-direction with 950 TPM, and another CSP filament covered the previously AN covered SSW in the S-direction with 950 TPM. The conductive composite yarns were all manufactured on a hollow spindle spinning machine.

Production of elastic warp-knitted fabric

Firstly multi-ply functional hybrid yarn A was prepared using BC-PET and CSP filaments with different proportions. Multi-ply hybrid yarn B was prepared with conductive composite yarn and viscose staple fiber spun yarns with fixed proportions. The main purpose of viscose and crisscross-section polyester yarns in the fabric was to increase the moisture absorption and sweat releasing function. Secondly wrap-knitted fabrics were fabricated using a crochet machine (Dah Heer Industrial Co., Ltd., Taiwan). Before the PET warp yarns were wound into a needle hook and loops formed with the rubber thread (model: 37#), multi-ply functional hybrid yarns A and B were firstly fed by back and front feeders alone in the weft direction, respectively (***Figure 1***). As a result, hybrid yarn A and B were inserted between the rubber thread and warp yarn loop as the back and front in the wrap-knitted fabrics, respectively (***Figure 2***). The blending ratio was varied for bamboo polyester filaments in hybrid yarns A to assess the far infrared emissivity and anion density effect and EMSE. Microscopic images of the back (a) and front (b) of the elastic warp-knitted fabric produced are shown in ***Figure 3***. Details of the warp-knitted fabrics produced are given in ***Table 1***.

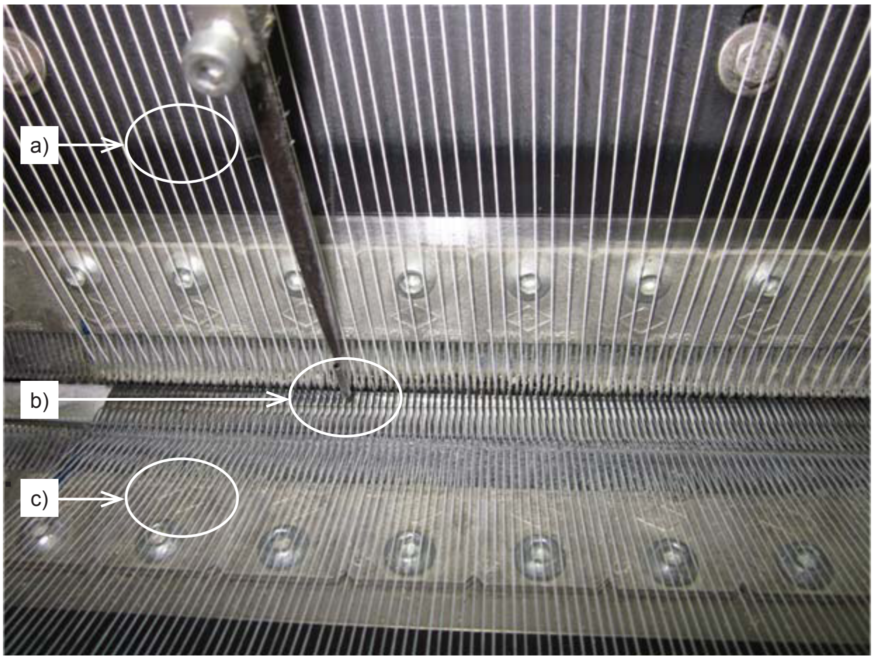

Figure 2. *Schematic of elastic warp-knitted fabric; a) rubber thread, b) front feeder, c) PET warp yarn.*

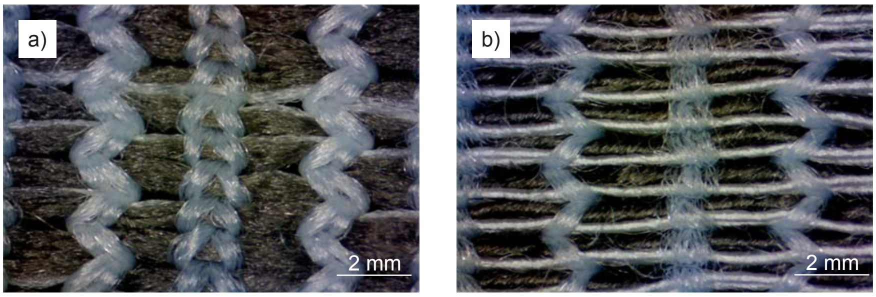

Figure 3. *Microscopic images of back (a) and front (b) of elastic warp-knitted fabric produced.*

Table 1. *Specification of elastic warp-knitted fabric samples produced;* ***Note****: BC-PET: bamboo charcoal polyester filament (150D/150F), CSP: crisscross-section polyester filaments (75D/48f), CCY: conductive composite yarn (300D), VY: viscose filament (166D), PET: polyester filament (150D/144F).*

Sample cold	Multiple hybrid yarns composition inserted		Density		
	Hybrid yarn A count and proportion	Hybrid yarn B count and proportion	Wales, cm	Weft, cm	Weight, g/cm
K1	600 denier/ 4BC-PET	580 denier/CCY: 2VY	6.1	20.5	51.4
K2	600 denier/3BC-PET:2CSP	580 denier/CCY: 2VY	6.2	20.1	52.2
K3	600 denier/2BC-PET:4CSP	580 denier/CCY: 2VY	6.1	20.6	51.1
K4	600 denier/1BC-PET:6CSP	580 denier/CCY: 2VY	6.3	20.1	49.8
K5	600 denier/8CSP	580 denier/CCY: 2VY	6.0	20.4	49.9
K6	600 denier/4PET	600 denier/4PET	6.2	20.7	51.8

EMSE test

The EMSE of the EM shielding fabric was assessed according to the ASTM D4935-99 [11] test method to measure the EMSE of the elastic warp-knitted fabrics fabricated. A Vector Network Analyzer (HP Agilent Co., Ltd., 8753B, USA) and shielding effectiveness test fixture (Electro-Metrics, Inc., EM-2107A, USA) were used to measure the EMSE with respect to decibels (dB).

The basic characteristic of the EM shielding fabric is its attenuation property towards an elecromagnetic wave. When an EM wave passes through a shielding material, the power of the wave is divided into three parts, namely reflection (P_{ref}), absorption (P_{abs}) and transmission (P_{trans}). Thus the shielding effectiveness of the fabric was assessed using the formula shown below [12, 13]

$$EMSE(dB) = 10 \log (P_{inc}/P_{trans}) \quad (1)$$

Figure 4. FIR emissivity tester.

where, P_{trans} represents the power transmitted and P_{inc} denotes the incident power.

Air permeability test

The air permeability of elastic warp-knitted fabric was evaluated according to ISO 9237:1995 using a FX-3300 air permeability tester (TESTEST INSTRUMNETS, Germany). The air pressure differential between the two surfaces of the material was 100 Pa [14].

FIR emissivity test

A TSS-5X tester (Japan Detector Co, Ltd., Japan) was used to measure the FIR emissivity as specified in FTTS-FA-010. The FIR emissivity of each sample was tested 20 times in different positions to obtain the mean values as shown in ***Figure 4***.

Anion density test

An anion tester - ITC-201A was provided by Andes Technology Corporation (Japan). A specimen was cut into a 300 mm 200 mm rectangle and then placed into a testing box to determine the anion density. The dimensions of the testing box were 300 × 200 × 200 mm.

Full relaxation treatment

All the fabrics were washed thoroughly, briefly hydro-extracted for 1 minute and then tumble dried for 60 minutes at around 70 °C. After washing and drying, the samples were then placed in standard atmospheric conditions (20 ± 2 °C and 65 ± 5% relative humidity) for 48 h. All tests were performed under standard ambient conditions [15].

Results and discussions

FIR emissivity of the fabric K-X series

Bamboo charcoal polyester filaments (BC-PET) have been widely applied in functional clothing because of their good FIR emissivity and anion release properties [16]. FIR rays, one type of infrared ray, have a wavelength ranging from 2.5 to 1000 μm. The FIR emissivity mechanism of the BC filament is the BC particle in the PET being able to absorb heat from the human body and release FIR at a specific wavelength (4 - 14 μm), which is easily absorbed by the body. When FIR enters deep into the human dermis, it can accelerate blood circulation, cell metabolism and nutrient consumption. Thus when BC filaments are used in electromagnetic shielding textiles, the protective clothing produced will not only provide an EM shielding effect but also possess a healthcare function.

To assess the FIR emissivity of elastic warp-knitted fabrics produced with different proportions of BC-PET content, a TSS-5X tester was used to test the back of the fabric, which was closed to the skin when wearing. ***Figure 5*** depicts the FIR emissivity of the K-X series of elastic warp-knitted fabric. It was found that elastic warp-knitted fabric K1 displayed the highest FIR emissivity, whereas the fabric K6 - the lowest, which was mainly due to fabric K1 having the most BC-PET filaments in the fabric, whereas fabric K6 was made from PET completely. Although the elastic warp-knitted fabric K4 having the lower BC-PET filaments in hybrid yarn A compared to fabric K1-K3, FIR emissivity of the fabric K4 was also over 0.93. This was due to the presence of rubber thread in the walewise direction of the elastic warp-knitted fabric, which resulting in fabric K4 also possessing many BC-PET filaments per unit area. Moreover it should be noted that fabric K5 showed higher FIR emissivity than fabric K6, which may be due to the fact that the conductive yarn was wrapped using BC-polyester filament

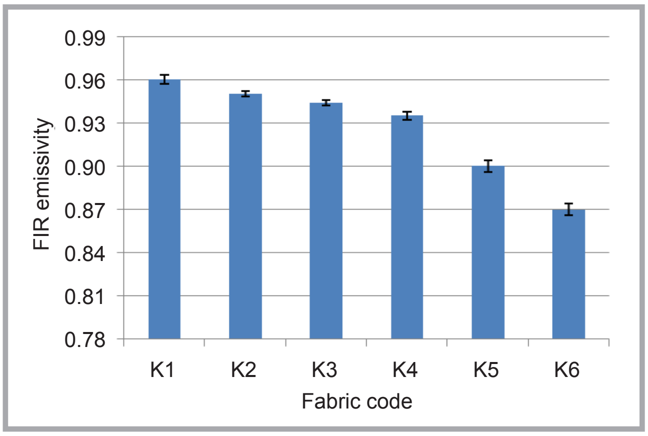

Figure 5. FIR emissivity of K-X series of elastic warp-knitted fabric.

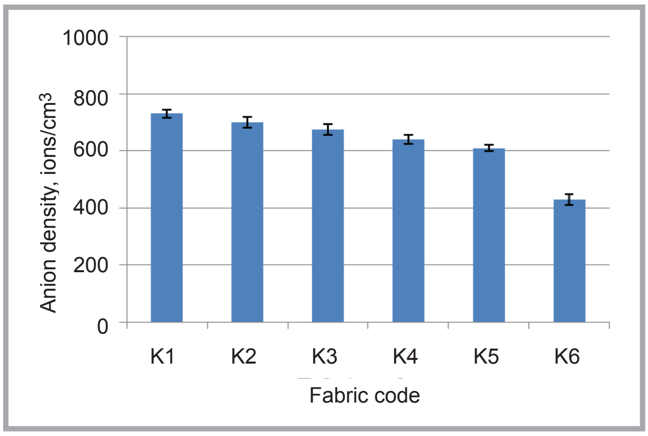

Figure 6. Anion density of K-X series of elastic warp-knitted fabrics.

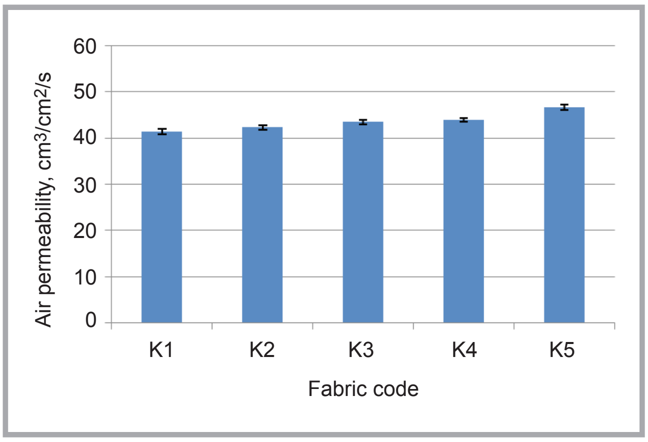

Figure 7. *Air permeability of K-X series of elastic warp-knitted fabrics.*

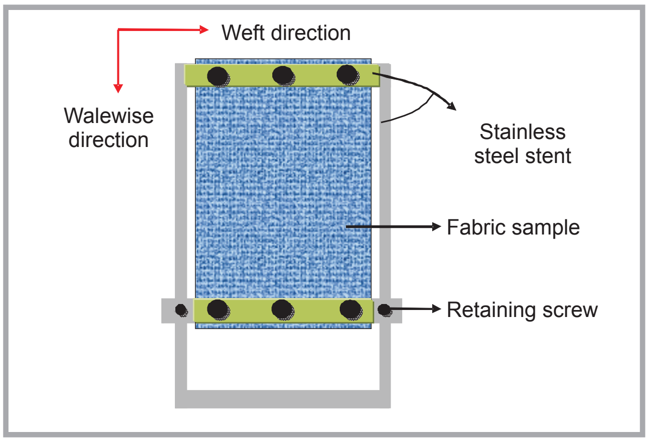

Figure 9. *Schematic of tensile fixtures.*

as outer wrapped yarns. Fabric K5 also contained BC-PET filament, therefore the fabric displayed a higher FIR emissivity compared to fabric K6.

Anion density of ic K-X fabric series

BC-PET will not only release FIR but also release anion, which is beneficial to the health by acting on the parasympathetic nervous system to relax the nerves [17]. ***Figure 6*** shows the variation in anion density for the K-X series of warp-knitted fabric fabricated. It was found that as the BC-PET content decreased, the anion density of the warp-knitted fabric gradually decreased. When the fabric did not contain BC-PET, the anion density of fabric K6 was only 420 ions/cm^3. Thus the presence of BC-PET in the warp-knitted fabrics was beneficial to increase anion density. Therefore the elastic warp-knitted fabrics produced possessed better healthcare than those made from common PET filaments.

Air permeability of K-X fabric series

As is known, sweat evaporation is mainly through the fabric space by means of diffusion in air from one to another side of the fabric. Hence air permeability is an important factor in the comfort of a protective garment as it plays a role in transporting moisture vapour from the skin to the outside atmosphere [18]. Moreover the air permeability also influences other properties of the protective garment such as warmth and protection against wind. Hence air permeability plays an important role in the functional properties of EM shielding clothing.

Figure 7 shows the variation in air permeability of elastic warp-knitted fabric (K1 - K5). It was found that the air permeability of the K-X fabric series increased gradually with an increasing CSP content in the fabrics. This was because BC-PET textured filament 150 den/144 f had more monofilaments than in the cross-section of filament 75 den/48f at the same linear density. Hence BC-PET will produce a higher resistance than CSP because of the loose structure. Despite the presence of rubber thread in the warp-knitted fabric, the air permeability decreased; all the values of air permeability were over 40 cm^3/cm^2/s, which could meet the need of daily activities.

EMSE of ic K-X fabric series

Figure 8 shows the EM shielding behaviour of the warp-knitted K-X fabric series in the frequency range of 3000 MHz to 3 GHz. Overall the EMSE of fabric K6 was almost zero within the frequency range of 300 KHz to 3 GHz, which was due to it being made of PET yarn, which has inherent electrical insulation and transparency to electromagnetic radiation [2]. Fabrics K1-K5 all show a certain extent EM shielding effect because of the presence of the conductive composite yarn in them. From ***Figure 8*** it was found that all the elastic warp-knitted fabrics produced displayed a similar EMSE level and a maximum of -20 to -40 dB was obtained in the low-frequency range of 233 - 563 MHz. Since the fabrics were all fabricated using the same function hybrid yarn B as the front, fabrics K2, K3, K4 & K5 show a similar EMSE level. Moreover as conductive composite yarn is only present in the weft direction of the warp-knitted fabric, the conductive metal wire could not form a conductive web. Hence the EMSE of the fabric produced was not ideal.

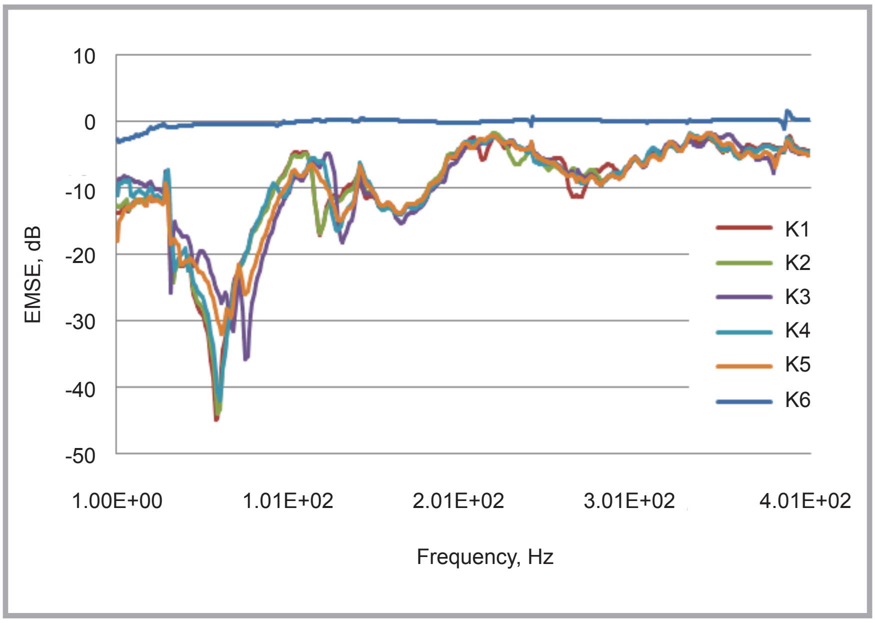

Figure 8. *EMSE of K-X series of elastic warp-knitted fabrics.*

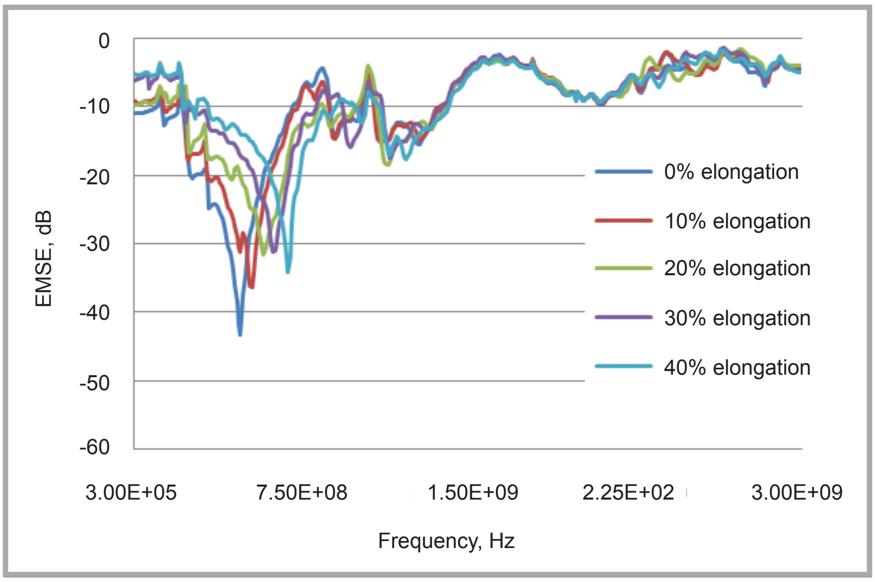

Figure 10. *Effect of elongation on the EMSE of fabric K1.*

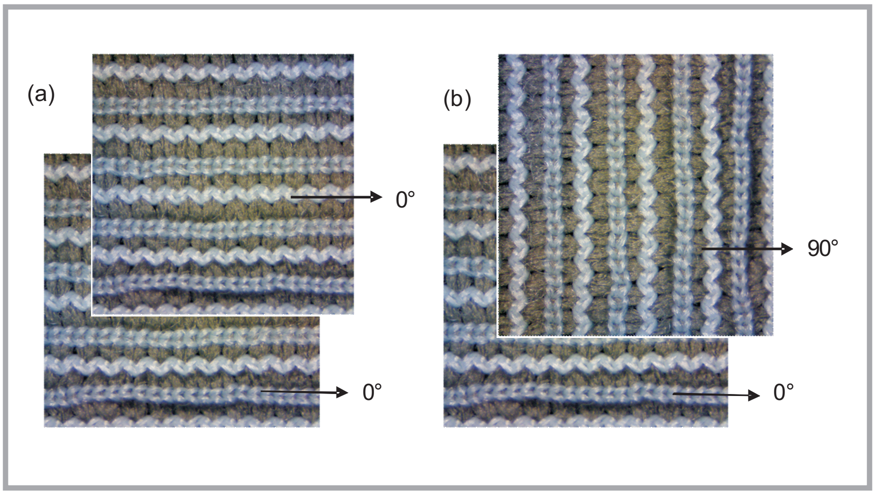

Figure 11. *Schematic of two-layer elastic warp-knitted fabrics at (a) 0°/0° and (b) 0°/90° lamination angles.*

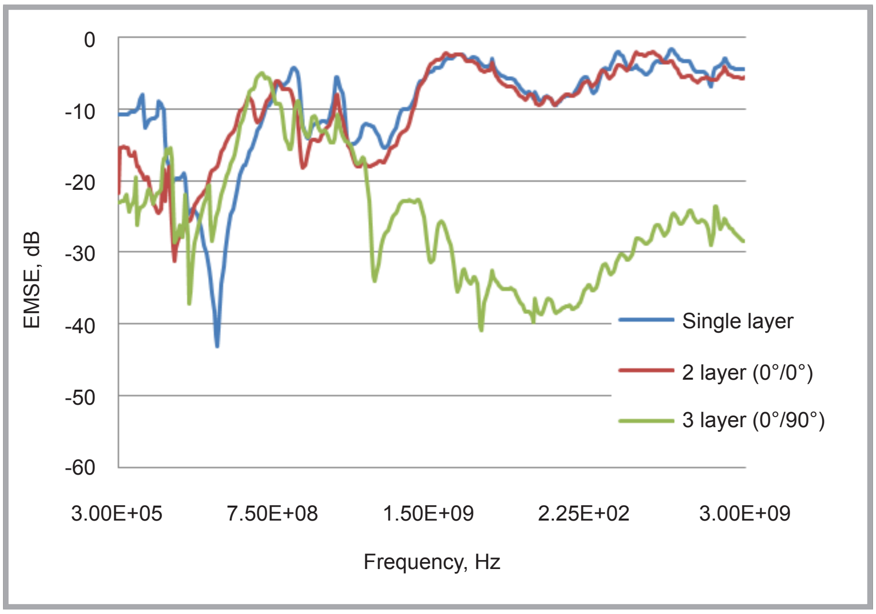

Figure 12. *EMSE of fabric K1 with different layers and lamination angles.*

Effect of elongation on EMSE of elastic warp-knitted fabric produced

When protective garments are subjected to tensility, the fabric will become elongated and deformed in the process of the wearer's normal activity. Therefore the study on the EM shielding effect at different elongations of the elastic fabric had very important practical significance. Thus, in this work, we studied the EMSE of the elastic warp-knitted fabric produced in the elongation range of 10 - 40%, which represents simple and ordinary body movement expanding the skin [19]. Since only rubber thread is present in the wale and weft directions of hybrid yarns A and B, having no elasticity, we only studied the effect of elongation on EMSE shielding behaviour in the wale direction. After considering the fact that the warp-knitted fabric produced had similar elongation and EMSE, we chose fabric K1 as representative. ***Figure 9*** shows the apparatus used to stretch the elastic warp-knitted fabric. From ***Figure 10*** it was found that the EMSE of fabric K1 displayed almost the same EMSE at different elongations. However, it was observed that the EMSE decreased with increasing elongation at a low-frequency range of 300 MHz - 0.75 GHz, which might due to the conductive metal wire not being able to form a conductive net, thus the fabric could not be effective against an EM wave. Thus the EM shielding behaviour of the elastic warp-knitted fabric produced displayed no marked variation when the changing metal mass per unit only.

Effect of lamination angles and lamination numbers on EMSE

In literature [20, 21], some researchers stated that when conductive metal wires were formed in a grid in fabric or laminated fabrics, they displayed the best EM shielding behaviour, especially for high-frequency EM waves. Hence to increase the EMSE of fabric K1, we used two layers of K1 fabric with a 0°/90° lamination angle to obtain at least -20 dB EMSE values across a wide range of frequencies. ***Figure 11*** shows the lamination method with 0°/0° and 0°/90° lamination angles. From ***Figure 12*** it was found that two layers of warp-knitted fabric K1 with a 0°/0° lamination angle could not significantly improve the EMSE compared to single-layer fabric K1. Again this was due to the conductive metal wire incorporated in the weft direction not being able to form a conductive net with a 0°/0° lamination angle. However, a dramatic variation in EMSE appeared when there were two layers of the fabric with a 90° interval. It was found that an EMSE of -20 to -40 dB was obtained within the high frequency range of 1.2 to 3 GHz. This phenomenon was attributed to the conductive metal wire having formed a metal grid, which was very effective against EM waves. A two-layer laminated fabric was enough to satisfy people's needs against EM waves in daily life.

Conclusions

In this research work, elastic warp-knitted fabric was produced using multi- functional hybrid yarn A and B as weft yarns, which were used as the front and back of the warp-knitted fabric, respectively. The research results concerned EM shielding properties of the warp-knitted fabrics and other functional properties such as FIR emissivity, anion release and air permeability. The following conclusions were made:

1. It was found that the FIR emissivity and anion density are all over 0.93 and 600 ions/cm^3 for fabrics K1, K2, K3 and K4, which resulted in the EM shielding fabric produced having a better healthcare function than common fabrics.
2. The warp-knitted fabrics produced displayed similar EM shielding behaviour among the K-X fabric series, which was only attributed to the weft yarn of the fabric having conductive metal wire.
3. In this study, the EMSE of fabric K1 displayed no significant difference when the fabrics were elongated in the wale direction alone.
4. The EMSE of two layer fabrics K1 with 0°/90° lamination angles showed a dramatic variation compared to those with 0°/0° lamination angles. Variation in the EMSE of the lamination fabric was due to the metal wire forming a metal grid structure in the lamination fabrics with a 90 degree interval.
5. The method of producing multifunctional elastic EM shielding textile on a crochet machine is an innovative one. The test results indicate that the elastic warp-knitted fabrics produced could be used as EM shielding protective clothing to protect the human from EM radiation originating from household electronic devices.

Acknowledgements

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