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Design and Manufacturing of Fabric Reinforced Electromagnetic Shielding Composite Materials

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ABSTRACT

There is an increasing need to develop new materials for shielding against electromagnetic pollution that result of the change in our life styles. In this study, a high performance textile based composite material that provides effective electromagnetic protection is presented to meet this demand. The over all study was planned in two parts. This paper is the first part of the study and it covers the stages of designing, manufacturing and testing for electromagnetic shielding applications of a composite material. The second part that is planned to be presented in another paper will cover some tests like tensile strength, elongation, durability, flammibility etc. The base textile material is a weft knitted fabric manufactured by using a hybrid yarn consists of polyamid and kevlar 49 yarn plied with a stainless steel wire on a winding machine. Various weft knitted structures were processed by a hot press to obtain 1.5-3.0 mm thin composite layer forms. The Electromagnetic shielding effectiveness (EMSE) measurement in 30-3000 MHz frequency band showed that a shielding performance of 20-60 dB could be achieved depending on the thickness and structure of the composites.

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KEYWORDS

Composite, electromagnetic shielding; polymer, knitting

1. INTRODUCTION AND BACKGROUND

Use of electrical and electronic devices emitting electromagnetic waves; extends from commercial and scientific electronic devices used in our daily lives to aviation systems and military electronic products [1]. Rapid developments in today's technology cause performance enhancement of mobile phones, wearable smart devices, computers, wireless systems, health devices, radars and so on [2].

In addition to facilitating human life, the increase in performance has brought up the problem of electromagnetic pollution. Electromagnetic interference can disrupt the function of electronic devices in the environment, as well as expose biological species to radiation damage [3]. In recent studies, many radiation damage caused by electromagnetic waves on living things have been reported [4]. Electromagnetic shielding (EMI) is the process of controlling electromagnetic interference by blocking field radiation with barriers made of conductive or magnetic materials [5]. The effective electromagnetic shielding material is characterized by high electrical conductivity and high dielectric constant. Both of these properties are found mostly in metals. Although the protection properties of metals are satisfactory, they are highly costly and sensitive to corrosive environments [6-8]. Therefore, in recent years, electromagnetic protective materials have been designed and manufactured as an alternative to metals [9]. In particular, studies are conducted on polymer-based conductive composites as an attractive alternative to conventional metal materials. Conductive composite materials have advantages such as light weight, corrosion resistance and ease of design compared to metal materials.

Polymer matrix composites constitute a wide range of products. They may be reinforced with conductive fiber, conductive particle, conductive yarn or conductive fabric.

The interest for textile and textile backed materials is increasing day by day in electromagnetic shielding applications due to their processability, drapeability, flexibility and impact energy absorption properties [10- 12]. Fiber or fabric reinforced composite materials began to play

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important roles for EMI shielding applications in especially aerospace, automotive and electronic instrument tecnology [13-16]. Some fiber, yarn and fabric parameters on electromagnetic shielding in textile based composites are investigated by many researchers.

Cheng and others 2000; investigated the EMSE of stainless steel/glass fiber polyamid composites and reported that the ratio of stainless steel mainly affected the EMSE of composites [17].

Duran and Kadoglu 2015; studied the effect of some yarn and fabric parameters on electromagnetic shielding and reported that a shielding effectiveness up to 48 dB was obtained [18].

Su and Chern 2004, studied on the electromagnetic shielding properties of fabrics consisted of stainless steel and reported that denser structures having much stainless steel had higher EMSE values. They also reported that fabric consisted of core yarn had higher EMSE than cover yarn and the plied yarn [19].

Safarova and Militky 2014, studied on metal/m-kevlar 49 fabrics. They stated 35 dB EMS values for samples including highest conductive component [20].

Another study was done by Ortlek, Alpyildiz and Kilic, 2013. They investiagated the EMSE of some knitted structures by the anechoic chamber with aperture method and determined that SE is effected from conductive amount, stitch length, frequency and the orientation of the fibers [21].

In most of the studies referred to above, different fabric structures, different yarn types and different polymer matrices have been tested. In most of these studies, EM shielding values of less than 50 dB were obtained. In this paper, the electromagnetic shielding performance of knitted polymer composites, especially manufactured from weft in-laid 1x1 rib structure and weft in-laid plain knitted structure, having maximum 60 dB are investigated and this was the originality and the difference of this study from the other studies. These two knitting structures, consisted of kevlar/PA/stainless steel, have never been studied for electromagnetic shielding applications. The composites developed in this study are consisted of Kevlar that is a very lightweight, carbon-based, high-strength and high temperature resistant material. The other material in the composite is stainless steel that is a cheap, conductive and high-strength material. Therefore, the developed composite material exhibits a satisfied electromagnetic shielding. Kevlar, stainless steel and polyamide were first brought together in this study and designed as a composite material. So this was the second difference of the study from other studies. This paper aims to produce a composite material that combines flexible, lightweight, high temperature based, durable and electromagnetic shielding in one material for many engineering applications. For this aim, the study is planned in two parts. In the first part; study covers the stages of designing, manufacturing and testing for electromagnetic shielding of the composite material. In the second part; study will cover some tests like tensile strength, elongation, durability, flammibility etc.

2. EXPERIMENTAL

2.1. Preparation of conductive yarn

Conductive yarns used for fabric samples were produced by a yarn winding machine. The hybrid yarn was composed of 0.15 mm single stainless steel wire (SS), Nm 18 Kevlar yarn and 300/70 denier/filaments Polyamid yarn.

2.2. Preparation of knitted samples

Knitted fabrics were manufactured on Passap seven gauge flat knitting machine. Six different structures detailed in Figure 1 were produced for this work (Figure 1). In Figure 2, the loop formations of knitted structures were given.

Stainless steel wire was selected as conductive filler because of its high conductivity. Kevlar yarn was the reinforcement material due to its high tensile strength and polyamid as the matrix material for its thermoplastic properties.

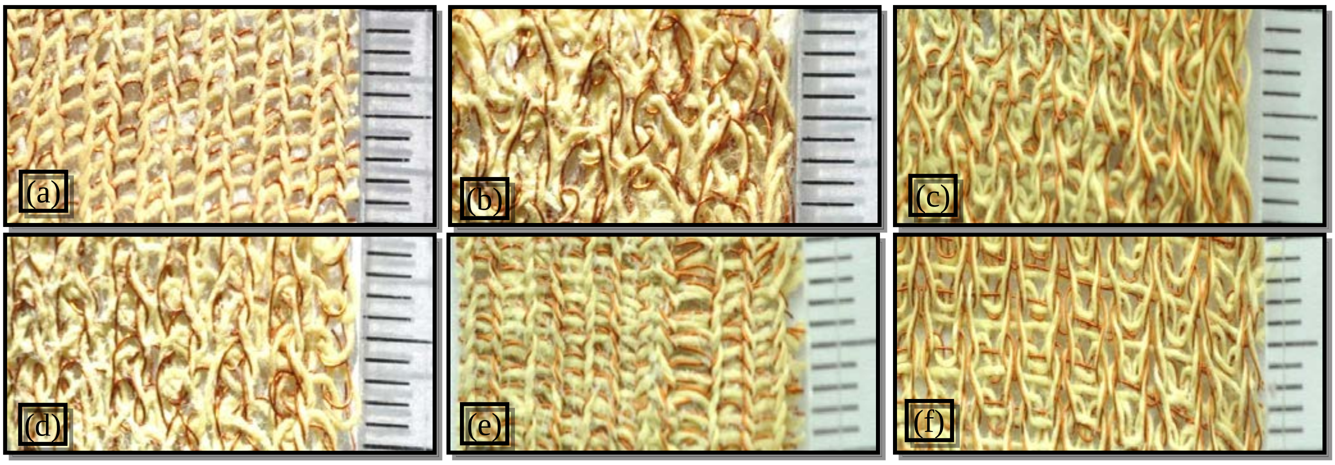


Figure 1. Six knitted samples a) (C1) plain knitting b) (C2) half cardigan c) (C3) milano d) (C4) 1X1 rib e) (C5) weft in-laid 1X1 rib f) (C6) weft in-laid plain knitting (The scale shows 1 mm).

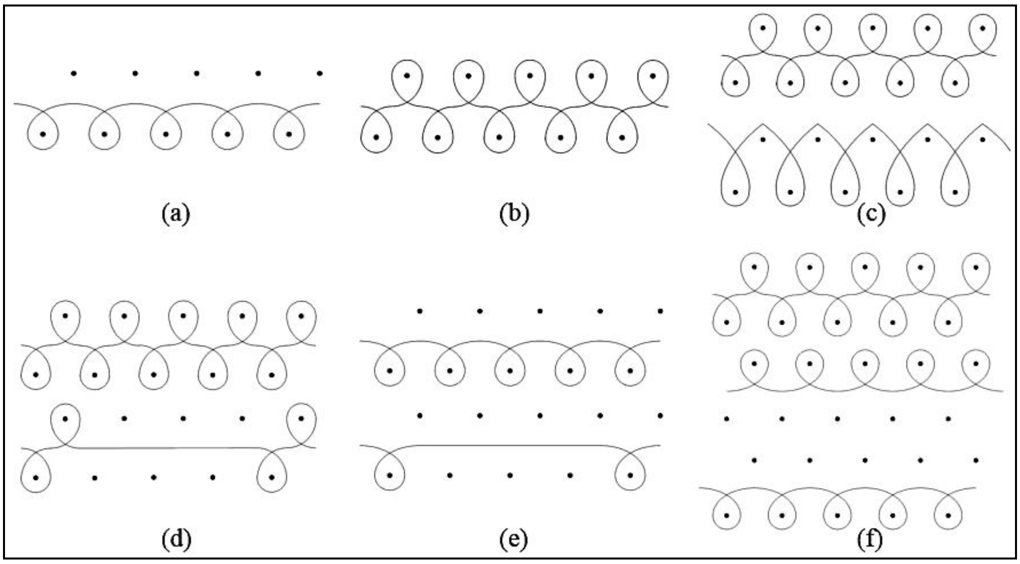


Figure 2. Loop formations of six knitted sample structures a) (C1) plain knitting b) (C4) 1x1 rib c) (C2) half cardigan d) (C5) weft in-laid 1X1 rib e) (C6) weft in-laid plain knitting f) (C3) Milano.

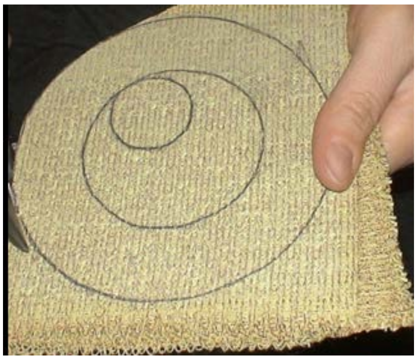
2.3. Composite manufacture

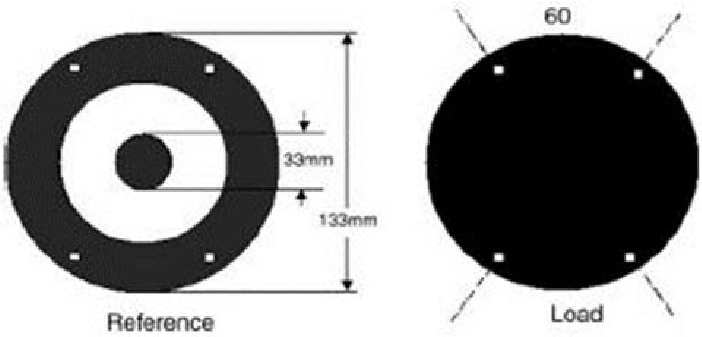
All composite laminates were manufactured by a hot press with 4 plies and 0º/90º/0º/90º lamination angle. The laminates transactioned at 260°C and under 15 kg/cm^2 pressure during 25 minutes. The polyamid fibers were melted under hot pressure and filled the gaps of the knitted fabrics. The test speciments, yarn combinations, fabric structures and the other properties describing the composites were detailed on Table 1.

It was achieved to manufacture the composites in sheets with thickness of 1.5-3 mm. The test specimens then machined to the dimensions having a circular area of 0.0136 m^2 with 133 mm radius (Figure 3).

Table 1. Properties of Composite Laminates

PROPERTIES OF COMPOSITES						
Composite	Yarn Combination	In Laid Yarn Combination	Structure	Course Density (loop/cm)	Wale Density (loop/cm)	Volume Fraction PA/SS/Kevlar(g)
C1	Kevlar/PA/0,15 mm SS	No Yarn	Plain Structure Knitted	7	4	0,82/4,1/1,36
C2	Kevlar/PA/0,15 mm SS	No Yarn	Half Cardigan Structure	2	3	0,93/4,65/1,55
C3	Kevlar/PA/0,15 mm SS	No Yarn	Milano Rib	3	3	0,95/4,7/1,56
C4	Kevlar/PA/0,15 mm SS	No Yarn	1x1 Rib Structure	4	2	0,84/4,2/1,4
C5	Kevlar/PA/0,15 mm SS	Kevlar/PA/0,15 mm SS	Weft in-laid 1x1 Rib Structure	4	2	0,87/4,3/1,4
C6	Kevlar/PA/0,15 mm SS	Kevlar/PA/0,15 mm SS	Weft in-laid Plain Knitted Structure	12	2	2,3/11,55/3,8





(a) (b)

Figure 3. (a) Composite test specimen (b) ASTM D4935 specimen geometry

2.4. EMSE Testing

EMSE tests were determined by coaxial test fixture related to ASTM D 4935. ASTM D 4935 measurement method is valid over a frequency range of 30 MHz to 1.5 GHz. But some researchers improved measurement adapters with coaxial cable diameter ratio of diameters different of 133/76 mm. This allowed the researchers to perform their measurements in the frequencies ranging up 30 MHz to 9 GHz [13]. The mechanism of coaxial test fixture is illustrated in Figure 4.

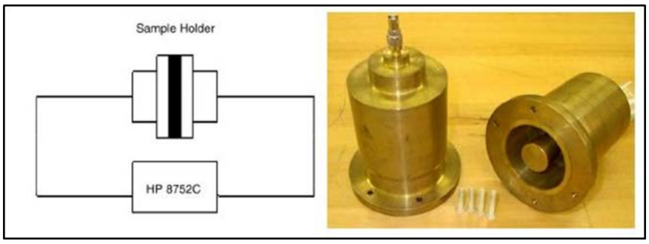


Figure 4. The schematic illustration of coaxial transmission line test fixture [14, 15]

Flanged coaxial test fixture is considered to be the most suitable test system since it is not based on an electrical contact with the samples.

Specimens were placed between the sample holders and EMSE test procedure was done according to the ASTM D 4935 standarts.

Tests were measured ten times for each sample at room temperature (22°C) between frequencies of 30 MHz-3 GHz and average values were determined. The values were evaluated with statistical analysis in one way Anova and the results were disscussed in Part 3.

3. RESULTS AND DISCUSSION

3.1. Morphology of composites

The morphology of composites was analyzed using a scanning electron microscopy (SEM). During the pressing process, the polyamid fibers were melted and covered the gaps of the kevlar fibers and stainless steel wire and the surface of the knitted fabric. Figure 5 shows the composite having the SS wire and kevlar yarn in the structure and micro-sized holes on the surface these holes were the result of scant amount of polyamid fibers in the structure. Fortunatelly micro-sized holes did not occure any more after increasing the amount of polyamid fibers in the structure.

No failure was observed for kevlar yarns and SS wires in the structure. The reinforced fabric gave an elastic structure to the composite and this was an advantageous property for composites compared with the other type of materials as polymer composites, metals etc.

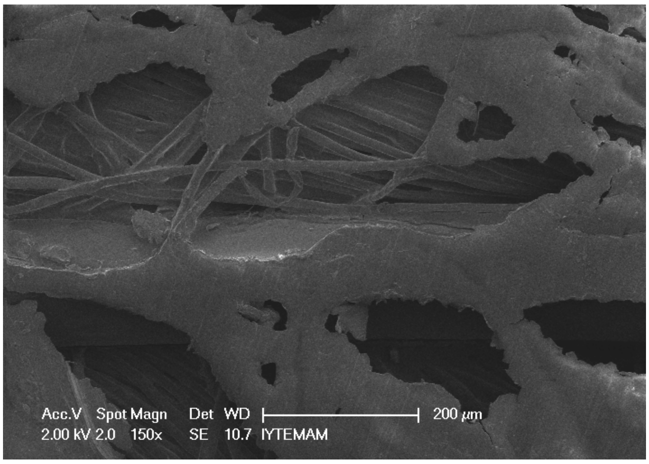


Figure 5. Photomicrograph of composite in 200 µm by SEM

The thickness of the composite fabrics after hot pressing process, was decreased by approximately 0,5 mm. The PA yarn was melted during the pressing process. The melted liquid interpenetrated through spaces in the fabric structure. So that the material took a semi-rigid form like an elastic panel.

Both the structure of the fabrics and the pressing process affect the thickness of the composites and the location of the stainless steel wires that leads a change in EMI shielding performances of the composites. Figure 6, Figure 7 and Figure 8 are the EMSE graphics of datas given on Table 2 at the frequency band of 30-500 MHz, 900-1800

MHz, 2000-2500 MHz and 30-3000 MHz respectively. In Figure 8, C1 had approximately 30-50 dB EMI shielding value in the frequency range of 30-500 MHz and this was the best EMI shielding value over the other five composites. This was due to the structure (plain knitted structure) of C1 composite had. In this structure the loops were close to each other and that means more area in the structure was placed with stainless steel wires. C3 and C6 composites followed C1 composite. C2 was the worst composite as an EMI shielding material. As it was presented in Table 1, C2 had a half cardigan knitted structure and the loops were far away from each other. Therefore, the results in this study were the expected results.

MHz band that is known as GSM band. In this frequency band, C6 was the best composite among the other composite types with 40-50 dB EMSE value. If Table 2 is observed carefully, it will be seen that C6 composite has the same properties as the other five composites except its structure. C6 was a weft in-laid plain knitting structure and it had more stainless steel yarn in it. C6 composite with 40-50 dB, had a ‘AAA- Good Degree’ in professional use and ‘AAAAA- Excellent Degree’ in general use according to the classification determined by the ‘Committee for Conformity Assessment of Accreditation and Certification on Functional and Technical Textiles’. The classification of electromagnetic shielding textiles is given on Table 2.

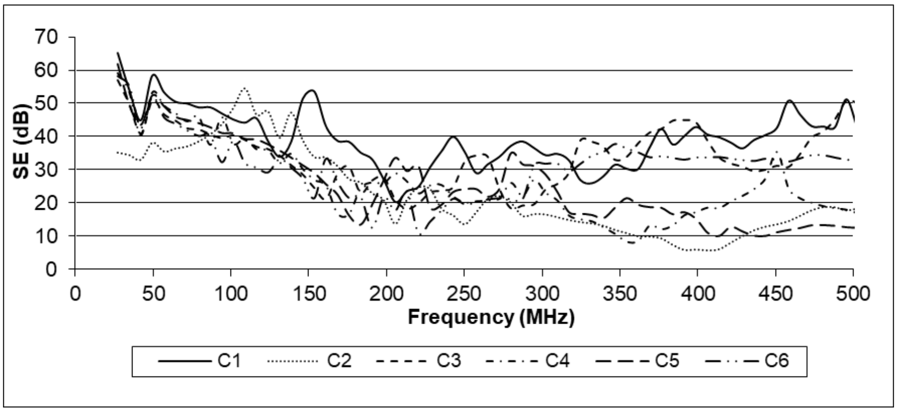


Figure 6. The graphical analysis of composites in the frequency range of 30-500 MHz.

Table 2. Classification of electromagnetic shielding textiles [11]

Type	Grade	Shielding effectiveness (dB)	Classification	Percentage of electromagnetic Shielding (%)
Class 1 Professional use	AAAAA	SE >60dB	Excellent	ES > 99.9999%
	AAAA	60dB ≥ SE > 50dB	Very good	99.9999% ≥ ES > 99.999%
	AAA	50 dB ≥ SE >40 dB	Good	99.999% ≥ ES > 99.99%
	AA	40dB ≥ SE > 30dB	Moderate	99.99% ≥ ES > 99.9%
	A	30 dB ≥ SE > 20dB	Fair	99.9% ≥ ES > 99.0%
Class II General use	AAAAA	SE > 30dB	Excellent	ES > 99.9%
	AAAA	30dB> ≥ SE > 20dB	Very good	99.9% ≥ ES > 99.0%
	AAA	20dB ≥ SE > l0dB	Good	99.0% ≥ ES > 90%
	AA	lOdB ≥ SE > 7dB	Moderate	90% ≥ ES > 80%
	A	7dB ≥ SE > 5dB	Fair	80% ≥ ES > 70%

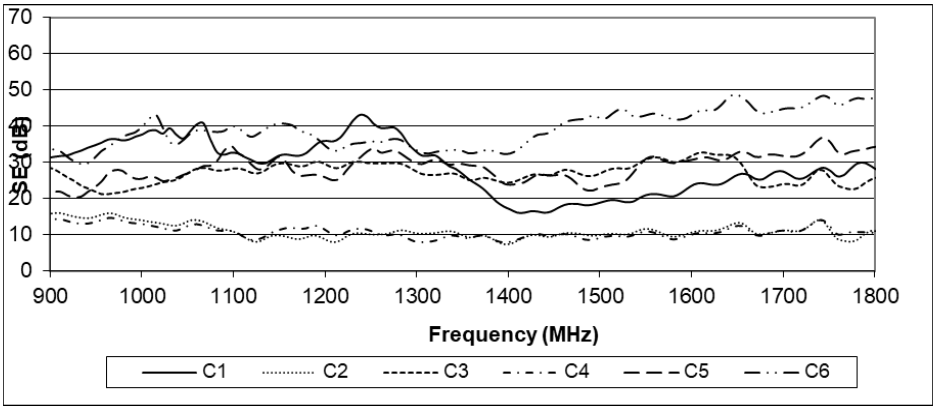


Figure 7. The graphical analysis of composites in the frequency range of 900-1800 MHz.

In Figure 8, the EMSE performances of the composites were analysed in the frequency range of 2000-2500 MHz which is known as 3G and Wi-Fi bands. In this band, C6 and C5 had the highest EMSE values respectively 50 dB and 40 dB. This can be explained with the in-laid yarn that is laid through the loop yarns in the same row horizantally. In- laid yarns in C6 and C5 composites had an active role in EMI shielding performance especially in high frequencies. As a result, C6 acted as anticipated but C5 composite had a surprising result. C5 had a loose loop formation in fabric form but in composite form the loops came more tight to each other owing to the pressing process. After the pressing process it acts as a plain knitting structure in EMSE tests.

The composites C1, C3, C4 and C2 follow them respectively. This was also an expected sutiation . Because the loop formation come looser from composite C1 to C2. So we can say that C6 had the best EMSE degree again as ‘AAAAA excellent’ in general use in 3G and Wi-Fi bands (2000-2500 MHz).

One-way ANOVA method was used to prove the significance of composite structure on the EMSE of composites. For the statistical evaluation mean values were taken as a basis. The mean values were evaluated at 5% significance level and the means were measured by Analysis of variance test for rejected hypothesis. The null hypothesis was established as ‘All means are equal’ and alternative hypothesis was established as’At least one mean is different’ and equal variances were assumed for the analysis. The results of the means were given on Table 3 and the Analysis of variance test results were given on Table 4 below. Factor level was determined as 6 and the factor values were as C1; C2; C3; C4; C5;C6. Pooled St. Dev is; 12,4394.

Table 3. Results of the means

Factor	Number	Mean	St Deviation	95% CI
C1	21	37,88	11,47	(32,51; 43,26)
C2	21	20,57	13,43	(15,20; 25,95)
C3	21	32,24	9,32	(26,86; 37,61)
C4	21	23,41	16,12	(18,04; 28,79)
C5	21	30,4	12,61	(25,03; 35,78)
C6	21	37,76	10,53	(32,38; 43,13)

Table 4. Analysis of variance

Source	Number	Adj SS	Adj MS	F-Value	P-Value
Factor	5	5436	1087,2	7,03	0,000
Error	120	18569	154,7		
Total	125	24005			

As the P-Value is less than 0,005; we can accept the alternative hypothesis and reject the null hypothesis. As the alternative hypothesis was established ’At least one mean is different’, the results of the ANOVA verify that the structure type is significiant on EMSE performance of the composites.

CONCLUSION

In this study, we produced composite structures in 1.5-3.0 mm thickness and investigated their EMSE performance. For this purpose, hybrid yarns were manufactured by plying a PA yarn, a kevlar 49 yarn and a stainless steel wire together on a winding machine. Then various weft knitted structures were produced on the flat knitting machine by using these hybrid yarns. Finally hot press process was applied to four plies of these weft knitted fabrics. The composite forms were obtained successfully without any holes occuring on the surface. The PA yarn played a role as a matrix after the hot pressing process by covering the gaps between the kevlar 49 yarns and stainless steel wires in the fabric. The manufactured composite forms had a stability of a panel and flexibility of a fabric to bend.

This study shown that, the in-laid plain knitting and in-laid 1x1 rib structures have the best EMSE barriers in high frequencies as they contain more amount of conductive stainless steel yarns because of the in-laid yarns in their structures. Structures have also an effect on EMSE of composites according to statistical analysis with one way ANOVA.

Fabric reinforced composites developed in this study have a great potential to be used in different aplications such as civil engineering, space engineering and marine engineering thanks to their high mechanical and EMI (upto 60 dB) shielding performance.

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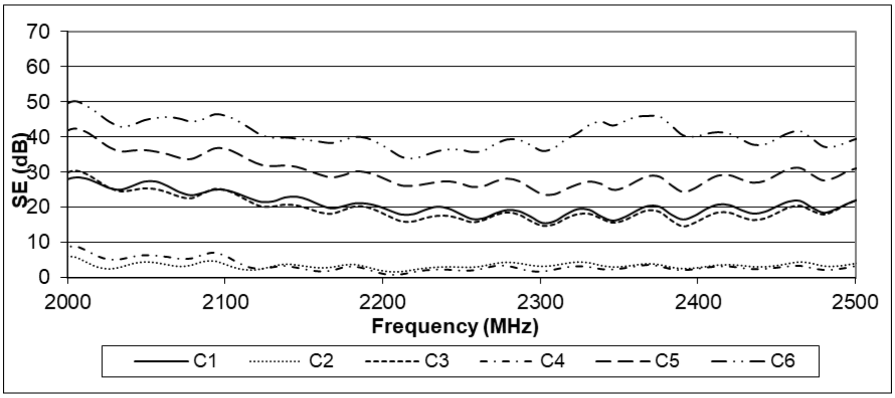

Figure 8. The graphical analysis of composites in the frequency range of 2000-2500 MHz.

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