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AN INVESTIGATION OF ELECTROMAGNETIC WAVE ABSORPTION POTENTIAL OF WOVEN FABRICS WITH STAINLESS STEEL WIRE

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Abstract

The growth of the electronic industry and the widespread use of electronic equipment in communications, computations, automations, biomedicine, space, and other purposes have led to many electromagnetic interference (EMI) problems as systems operate in close proximity. The rapid development of advanced electronic devices and applications has brought with it a growing interest in electromagnetic wave-absorbing materials. Many commercial and military applications, such as data transmission, telecommunications, wireless network systems, and satellite broadcasting, as well as radars, and diagnostic and detection systems, utilize and emit electromagnetic waves.

In recent years, electromagnetic (EM) waves in the 1–10 GHz range are broadly used in wireless communication tools and local area networks. In the future, the usable range of EM waves will tend to shift further to higher frequency regions with the development of information technology as well as electronic devices. As a consequence, the seriousness of problems such as EMI of electronic devices and health issues is ever rising.

This article investigates the electromagnetic wave-absorbing properties of stainless steel wire containing woven fabrics. Electromagnetic wave absorbing properties of woven fabrics consisting of yarns, which are made of finest stainless steel, wires and cotton fibers were fabricated by using the ring spinning methods. The woven fabrics with the same warp density but variable weft density were produced at the sample-weaving machine. Effect of the weft density and pattern on electromagnetic wave absorbing properties were investigated A coaxial transmission line method specified in ASTM D4935-10 was utilized to test the woven fabrics and the tests were carried out in the frequency range from 15MHz to 3000 MHz.

Keywords: *Electromagnetic shielding, electromagnetic wave absorbing, metal wire, weaving, woven fabric.*

1. Introduction

With the rapid growth of the electrical and electronic devices and accessories, which emit electromagnetic energy in the different frequency bands used in the markets, it becomes essential to limit and shield electronic equipment against all sources of interference due to all these electromagnetic energies. There is a growing need for setting limits on the electromagnetic emissions from these devices in order to minimize the possibilities of interfering with radio and wire communications [1,5]. Among the various solutions offered, textile products and textile-based composite materials have caught the attention of researchers for the versatility and conformability these textile structures provide. Increased awareness of EMI has led to the formulation of new regulations around the globe for the manufacturers of electrical and electronic equipment to comply with the electromagnetic compatibility requirements [3]. Many countries legislating new regulations so that the manufacturers of electrical and electronic equipment comply with the electromagnetic compatible (EMC) requirement. In USA the Federal Communications Commission (FCC) is entrusted with the responsibility of controlling the interference from and to wire and radio communications [1].

Many devices contribute to such exposure such as cell phones with frequencies of 900 and 1800MHz, microwave ovens of 2450 MHz, radar signal communication systems extending from 1 to 10,000 MHz, and FM/AM radiobroadcasts of 30-300 MHz and 300-3000 KHz, respectively. Cell phone use is particularly widespread [2].

Today, it is very important to reduce negatives effects caused electromagnetic waves on people, animals and environment. If an electromagnetic wave gets into an organism, it vibrates molecules to give out heat. In the same way, when an electromagnetic wave enters the human body, it will obstruct a cell's regeneration of DNA and RNA. Furthermore, it brings on abnormal chemical activities to produce cancer cells, and increases the possibility of leukemia and other cancers. Injuries by electromagnetic waves to the human body are the top priority of professionals and scholars, and we are most concerned with solving this problem [2,4]. For this, some conductive materials, the fabrics with metal fibre and metal wire, metal foils, conductive paints, lacquers and electroless plating are used to reduce the transmission of electromagnetic radiation that affects the human/equipments. This process is called as an "electromagnetic shielding". Electrically conductive textile surfaces are one of the shielding materials that are used to prevent harmful effects of electromagnetic waves. The lifetime and efficiency electronic devices can be increased through effective electromagnetic interference shielding. [6]

Electromagnetic wave consists of an electrical component and magnetic component perpendicular to each other and propagates at right angles to the plane. The waves are produced by the motion of electrically charged particles. These waves are also called "electromagnetic radiation" because they radiate from the electrically charged particles. They travel through empty space as well as through air and other substances. This is difficult to visualize, however the waveform has similar characteristics of other types of waves.

Although they seem different, radio waves, microwaves, x-rays, and even visible light are all electromagnetic waves. They are part of the electromagnetic spectrum, and each has a different range of wavelengths, which cause they waves to affect matter differently.

The range of wavelengths for electromagnetic waves from the very long to the very short is called the Electromagnetic Spectrum [7].

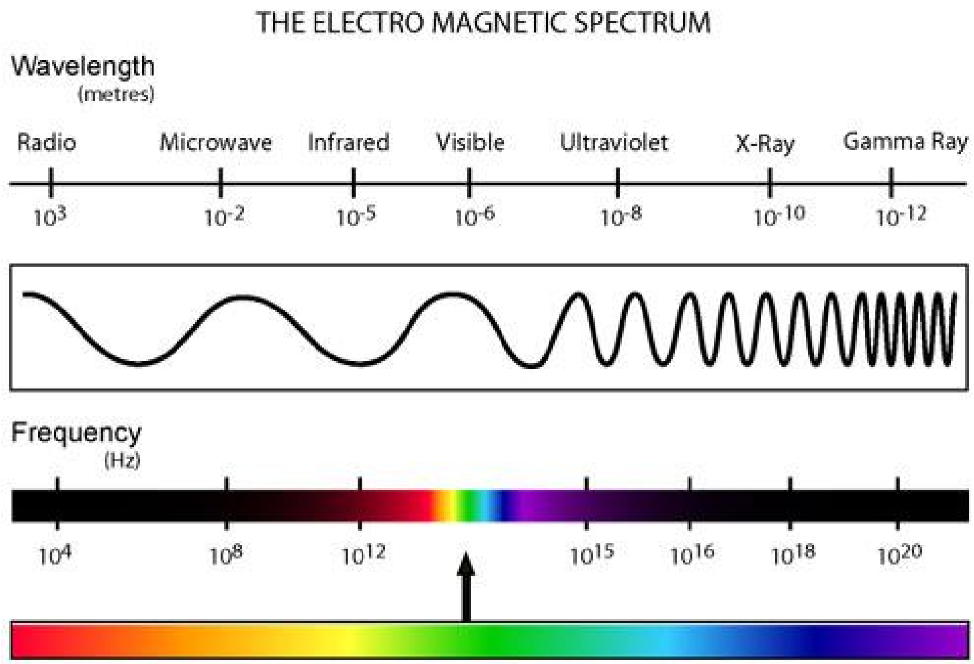


Figure 1: *Electromagnetic Spectrum*

When you listen to the radio, watch TV, or cook dinner in a microwave oven, you are using electromagnetic waves. Radio waves, television waves, and microwaves are all types of electromagnetic waves. They differ from each other in wavelength. Wavelength is the distance between one wave crest to the next.

Waves in the electromagnetic spectrum vary in size from very long radio waves the size of buildings, to very short gamma-rays smaller than the size of the nucleus of an atom.

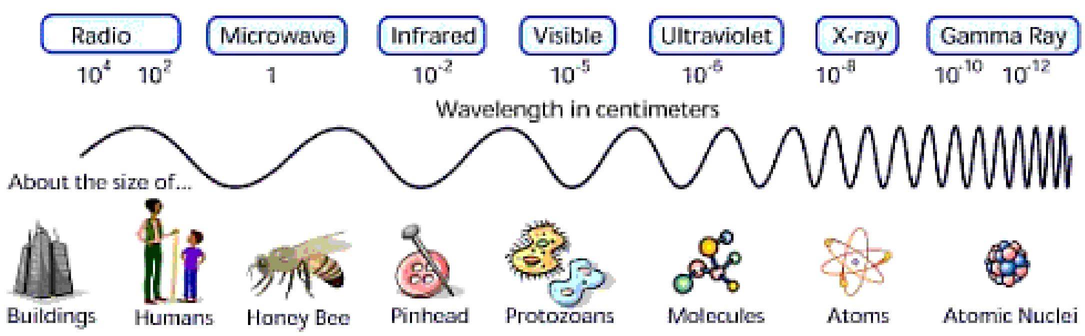


Figure 2: *Waves in the Electromagnetic Spectrum*

Radio waves have the longest wavelengths in the electromagnetic spectrum. These waves can be longer than a football field or as short as a football. Radio and TV have a wavelength of 1 mile (1.5 kilometer) or more. Radio waves do more than just bring music to your radio. They also carry signals for your television and cellular phone. Microwaves are used in telecommunication as well as for cooking food. Infrared waves are barely visible. They are the deep red rays you get from a heat lamp. Visible light waves are the radiation you can see with your eyes. Their wavelengths are in the range of 1/1000 centimeter.

Ultraviolet rays are what give you sunburn and are used in "black lights" that make object glow. X-rays go through the body and are used for medical purposes. Gamma rays are dangerous rays coming from nuclear reactors and atomic bombs. They have the shortest wavelength in the electromagnetic spectrum of about 1/10,000,000 centimetre.

The antennae on your television set receive the signal, in the form of electromagnetic waves that is broadcasted from the television station. It is displayed on your television screen. Cable companies have antennae or dishes, which receive waves broadcasted from your local TV stations. The signal is then sent through a cable to your house. Cellular phones also use radio waves to transmit information. These waves are much smaller that TV and FM radio waves.

Because radio waves are larger than optical waves, radio telescopes work differently than telescopes that we use for visible > light (optical telescopes). Radio telescopes are dishes made out of conducting metal that reflect radio waves to a focus point. Because the wavelengths of radio light are so large, a radio telescope must be physically larger than an optical telescope to be able to make images of comparable clarity. For example, the Parkes radio telescope, which has a dish 64 meters wide, cannot give us any clearer an image than a small backyard telescope.

In order to make better and more clear (or higher resolution) radio images, radio astronomers often combine several smaller telescopes, or receiving dishes, into an array. Together, the dishes can act as one large telescope whose size equals the total area occupied by the array.

Electrical and Electromagnetic waves emerge spontaneously. Electromagnetic waves are classified as a natural and man-made. Natural electromagnetic field consists of invisible waves, exists at the north and south direction around the sphere and helps to find direction to the birds and fishes. In addition to that, there are electromagnetic fields reflecting from man-made sources. Television antenna, radio station, roentgen devices which is source of x-ray, radio waves with high frequency, mobile telephone stations are shown between man-made sources. All electrical devices used at home and work offices are electromagnetic field sources. The field affect the electronic devices and can cause improperly operation.

Electromagnetic waves are transverse waves, similar to water waves in the ocean or the waves seen on a guitar string. This is as opposed to the compression waves of sound. All waves have amplitude, wavelength, velocity and frequency.

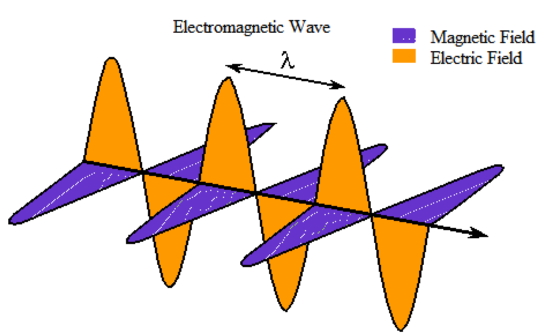


Figure 3: *Motion of the Electromagnetic Waves*

Amplitude

The amplitude of electromagnetic waves relates to its intensity or brightness (as in the case of visible light). With visible light, the brightness is usually measured in lumens. With other wavelengths the intensity of the radiation, which is power per unit area or watts per square meter is used. The square of the amplitude of a wave is the intensity.

Wavelength

The wavelengths of electromagnetic waves go from extremely long to extremely short and everything in between. The wavelengths determine how matter responds to the electromagnetic wave, and those characteristics determine the name we give that particular group of wavelengths.

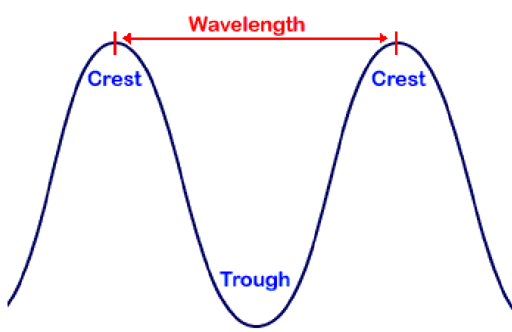


Figure 4: *Wavelength*

Velocity

The electromagnetic waves disperse the same speed in an air. The velocity of electromagnetic waves in a vacuum is approximately 186,000 miles per second or 300,000 kilometres per second, the same as the speed of light. When these waves pass through matter, they slow down slightly, according to their wavelength.

Frequency

The frequency of any waveform equals the velocity divided by the wavelength. The units of measurement are in cycles per second or Hertz.

Shielding fabrics are coated with Nickel Copper on woven, nonwoven, rip stop and taffeta fabrics. Showing excellent shielding effect, high conductivity and corrosion proof, it is mainly used to produce shielding tape or Gasket. And also used for making shielding garments, ESD(electric static discharge) garments and packing materials, shielding tents and shielding rooms. The lowest surface resistivity could reach at 0.005ohms/sq.We could backing hot melt adhesive and conductive adhesive as the customers request.

1.1. Shielding Effectiveness

Shielding can be specified in the terms of reduction in magnetic (and electric) field or plane-wave strength caused by shielding. The effectiveness of a shield and its resulting EMI attenuation are based on the frequency, the distance of the shield from the source, the thickness of the shield, and the shield material. Shielding effectiveness (SE) is normally expressed in decibels (dB) as a function of the logarithm of the ratio of the incident and exit electric (E), magnetic (H), or plane-wave field intensities SE(dB)=20log(E0/E1), SE(dB)=20log(H0/H1), and SE(dB)=20log(F0/F1) respectively [8].

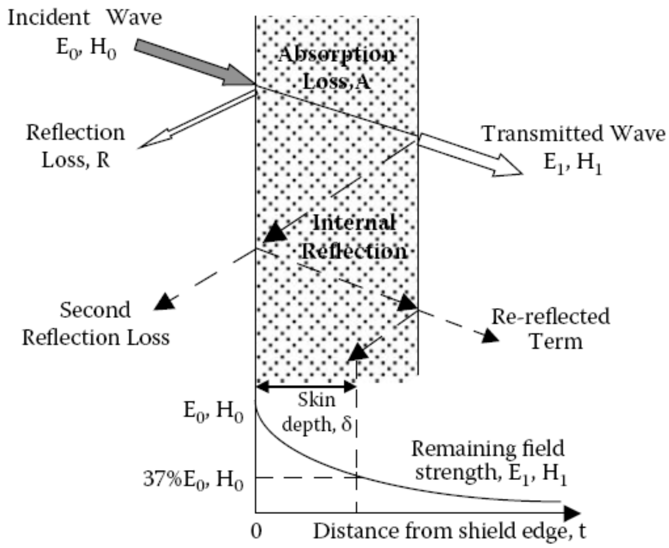


Figure 5: *Graphical representation of EMI shielding.*

With any kind of electromagnetic interference, there are three mechanisms contributing to the effectiveness of a shield. Part of the incident radiation is reflected from the front surface of the shield, part is absorbed within the shield material, and part is reflected from the shield rear surface to the front where it can aid or hinder the effectiveness of the shield depending on its phase relationship with the incident wave, as shown in Figure 1. Therefore, the total shielding effectiveness of a shielding material (SE) equals the sum of the absorption factor (A), the reflection factor (R), and the correction factor to account for multiple reflections in thin shields:

$$SE = R + A + B \qquad (1)$$

All the terms in Equation 1 are expressed in dB. The multiple reflection factor B can be neglected if the absorption loss A is greater than 10 dB. In practical calculation, B can also be neglected for electric fields and plane waves.

Absorption Loss

Absorption losses A are a function of the physical characteristics of the shield and are independent of the type of source field. Therefore, the absorption term A is the same for all three waves. When an electronic wave passes through a medium such as a shield, its amplitude decreases exponentially, as shown in Figure 1. This decay or absorption loss occurs because currents induced in the medium produce ohmik losses and heating of the material, and E1 and H1 can be expressed as (Ott 1988): E1= E0e-t/δ and H1= H0e-t/δ. The distance required for the wave to be attenuated to 1/e or 37% is defined as the skin depth, δ. Therefore, the absorption term A is given by the expression:

$$A = 20\ (t/\delta)\ \log\ (e) = 8.69\ (t/\delta) = 131\ t\sqrt{f\mu\sigma} \qquad (2)$$

where A is the absorption or penetration loss expressed in decibels; t is the thickness of the shield in mm; f is frequency in MHz; μ is relative permeability (1 to copper); σ is conductivity relative to copper in IACS. The skin depth δ can be expressed as:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (3)$$

The absorption loss of one skin depth in a shield is approximately 9 dB. Skin effect is especially important at low frequencies, where the fields experienced are more likely to be predominantly magnetic with lower wave impedance than 377 **Ω**.

Reflection Loss

The reflection loss is related to the relative mismatch between the incident wave and the surface impedance of the shield. The computation of reflection losses can be greatly simplified by considering shielding effectiveness for incident electric fields as a separate problem from that of electric, magnetic, or plane waves. The equations for the three principle fields are given by the expressions (Ott, 1988):

$$R_E = 321.8 + 10\log\frac{\sigma}{f^3 r^2 \mu} \qquad (4)$$

$$R_H = 14.6 + 10\log\frac{f r^2 \sigma}{\mu} \qquad (5)$$

$$R_p = 168 - 10\log\frac{f\mu}{G} \qquad (6)$$

where RE, RH, and Rp are the reflection losses for the electric, magnetic, and plane wave fields, respectively, expressed in dB; σ is the relative conductivity referred to copper; f is the frequency in Hz; μ is the relative permeability referred to free space; and r is the distance from the source to the shielding in m.

Multiple Reflection Correction Factor

The factor B can be mathematically positive or negative (in practice it is always negative), and becomes insignificant when the absorption loss A > 6 dB. It is usually only important when metals are thin and at low frequencies (i.e., below approximately 20 kHz). The formulation of factor B can be expressed as (Vasaka, 1956):

$$B(dB) = 20\ \log\left|1 - \frac{(K-1)^2}{(K+1)^2}\left(10^{-A/10}\right)\left(e^{-i227A}\right)\right| \qquad (7)$$

where A is the absorption loss (dB); K = ZS/ZH = 1.3 (μ/fr2σ)1/2; ZS is the shield impedance; and ZH is the impedance of the incident magnetic field. When ZH<< ZS, the multiple reflection factor for magnetic fields in a shield of t and skin depth δ can be simplified as (Ott, 1988):

$$B = 20\ \log\ (1-e^{-2t/\delta}) \qquad (8)$$

Consequently, the total shielding effectiveness for electric, magnetic, and plane wave fields can be obtained by Equation 1 with a combination of the related equations of absorption and reflection losses, as well as correction factor B.

2. Materials and Methods

2.1. Materials

2.1.1. Fabrication of Core-Spun Yarns

The yarn counts varied depending on thicknesses of stainless steel wire. Yarns were produced in the ring machine by core-spun method. Core-spun yarns have two components, which are core component and covering component. In this our study, the covering component is cotton fibers and core component is stainless steel wire. Properties of materials are given in Table 1 and Table2.

Table 1: *Characteristic of Metal Filaments*

Metal Fibers	Stainless Steel (SS)
Linear Density (micron)	50
Density (kg/dm^3)	7.9
DC Resistance (Ω/m)	735

Table 2: *Characteristic of Core-Spun Yarns*

Yarn Counts	Structure
Ne9/1	Cotton / 0.050mm SS

2.1.2. Fabrication of Weaving Fabrics

Produced yarns were formed into handloom machine. Kind of weave structures are namely plain, twill and Sateen. The woven fabrics are produced by considering three different weaves and two different weft density. Properties of weaving fabrics are given in Table 3.

Table 3: *Characteristic of Weaving Fabrics*

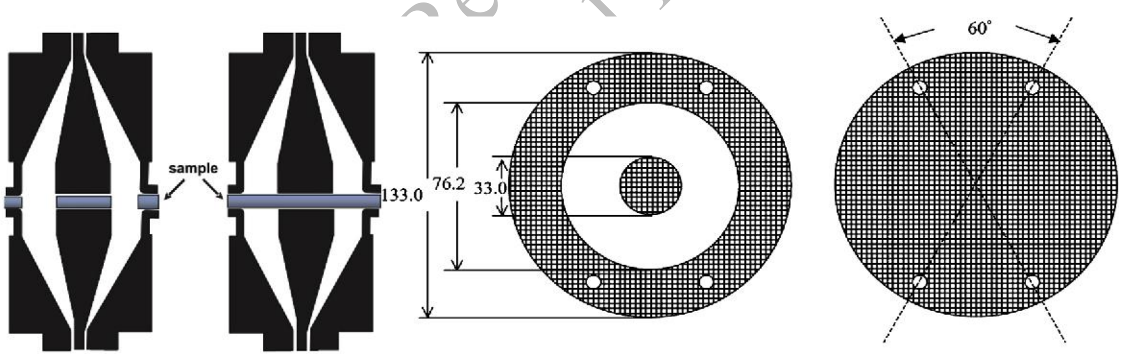
Fabric Code		Structure	Weft Density (Picks per/cm)	Warp Density (Picks per/cm)
PW13	Plain Wave	(1 x Cotton Ne10/1) + Ne9/1(Cotton / 0.050mm SS)	13	15
PW15	Plain Wave	(1 x Cotton Ne10/1) + Ne9/1(Cotton / 0.050mm SS)	15	15
SW13	Sateen Wave	(1 x Cotton Ne10/1) + Ne9/1(Cotton / 0.050mm SS)	13	15
SW15	Sateen Wave	(1 x Cotton Ne10/1) + Ne9/1(Cotton / 0.050mm SS)	15	15
TW13	Twill Wave	(1 x Cotton Ne10/1) + Ne9/1(Cotton / 0.050mm SS)	13	15
TW15	Twill Wave	(1 x Cotton Ne10/1) + Ne9/1(Cotton / 0.050mm SS)	15	15

2.1.3. EM Shielding Effectiveness (EMSE) Measurements

The electromagnetic shielding effectiveness of the produced needle punched nonwoven fabrics were determined with based on ASTM D 4935-10 the coaxial transmission line method for planar materials standard. A shielding effectiveness test fixture (Electro-Metrics, Inc., model EM-2107A) was used to hold the sample with a network analyzer generating and receiving the EM signals. This standard determined the shielding effectiveness of the textile structures using the insertion-loss method. The technique involved 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. [9, 10, 11] Figure 6 shows the EMSE testing apparatus.

Figure 6: *Set up of EMSE Testing Apparatus*

A reference measurement for the empty cell was required for the shielding-effectiveness assessment (Figure 7a). The reference sample was placed between the flanges in the middle of the cell, covering only the flanges and the inner conductors. A load measurement was performed on a solid disk shape which had a diameter the same as that of the flange (Figure 7b). The size of the cross section of reference sample (Figure 7c) and load sample (Figure 7d) are also shown in Figure3. The reference and load measurement were preformed on the same material.



(a) (b) (c) (d)

Figure 7: *A cross-section of the shielding effectiveness test fixture (a) reference sample in the jig and (b) load sample in the jig. Specific dimensions of the specimens for shielding effectiveness measurement (unit: mm), (c) Reference sample (d) Load sample*

The shielding effectiveness was determined from (Formula 9), which is the ratio of the incident field to that which passes through the material.

$$\mathrm{EMSE} = 10\log\left(\frac{P_1}{P_2}\right) \tag{9}$$

Where P1 (watts) is received power with the fabric present and P2 (watts) is received power without the fabric present. The input power used was 0 dBm, corresponding to 1 mW.

The reflectance (R_e) and the transmittance (T_r) of the composite were also measured and the absorbance (A_b) was calculated using following Eq. (10):

$$A_b = 1 - T_r - R_e \tag{10}$$

where, Re and Tr are the square of the ratio of reflected (Er) and transmitted (Et) electric fields to the incident electric field (Ei), respectively, as following Eqs. (11) and (12):

$$R_e = \left|\frac{E_r}{E_i}\right|^2 = |S_{11}(or\ S_{22})|^2 \tag{11}$$

$$T_r = \left|\frac{E_t}{E_i}\right|^2 = |S_{21}(or\ S_{12})|^2 \tag{12}$$

R_e and T_r were obtained by the measurement of S-parameters, S_{11} (or S_{22}) and S_{12} (or S_{21}) for the reflection and the transmission, respectively.

The shielding effectiveness measurements were carried out between 15MHz to 3000MHz. The measurement device consists of a network analyzer, which is capable of measuring incident, transmitted and reflected powers, and a sample holder. The shielding effectiveness is determined by comparing the difference in attenuation of a reference sample to the test sample, taking into account the incident and transmitted power.

Table4: *Evaluation of Electromagnetic Shielding Effectiveness for General Use [12]*

Grade	5 Excellent	4 Very Good	3 Good	2 Moderate	1 Fair
Percentage of Electromagnetic Shielding	ES＞99.9%	99.9%≧ES 99.0%	99.0%≧ES＞90%	90.%≧ES＞80.%	80%≧ES＞70%
Shielding Effectiveness	SE＞30dB	30dB≧SE＞20dB	20dB≧SE＞10dB	10dB≧SE＞7dB	7dB≧SE＞5dB

SE: Shielding Effectiveness (dB)
ES: Percentage of Electromagnetic Shielding (%)

Table 5: *Evaluation of Electromagnetic Shielding Effectiveness for Professional Use*

Grade	5 Excellent	4 Very Good	3 Good	2 Moderate	1 fair
Percentage of Electromagnetic Shielding	ES > 99.99999%	99.9999% ≥ ES > 99.999%	99.999% ≥ ES > 99.99%	99.99% ≥ ES > 99.9%	99.9% ≥ ES > 99.0%
Shielding Effectiveness	SE ≥ 60dB	60dB ≥ SE>50dB	50dB ≥SE>40dB	40dB ≥SE>30dB	30dB ≥SE>20dB

SE: Shielding Effectiveness (dB)
ES: Percentage of Electromagnetic Shielding (%)

3. RESULTS

The EMSE, reflection and absorption results obtained from measurements were commented by considering first, number of thread per cm at the same weaves (pattern) and then different pattern at the same number of weft thread per cm. As the number of weft thread per cm and pattern change, change in the EMSE, reflection and absorption results were shown in below graphics.

Reflectance and Absorbance Measurements

Absorbance (Ab), reflectance (Re) and transmission (Tr) values measured from woven fabrics produced with yarn reinforced stainless steel wire were shown in following figures (8-13). The 15-3000MHz frequency ranges were determined for evaluating the Absorbance (Ab) and Reflectance (Re) measurement values of woven fabrics. The evaluation of the absorbance and reflectance measurements of the woven fabric samples were carried out at low, medium and high frequency electromagnetic wave ranges.

Figure 8 and Figure 9 show Absorbance and Reflectance values of woven fabrics in the low frequency range of 15-600MHz. It can clearly be seen that the reflectance values increases as the frequency increases but the absorbance values decreases mostly.

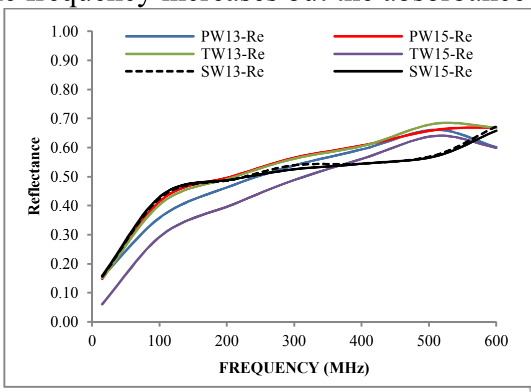


Figure 8: *Reflectance of different woven fabrics with weft density Between 15-600 MHz.*

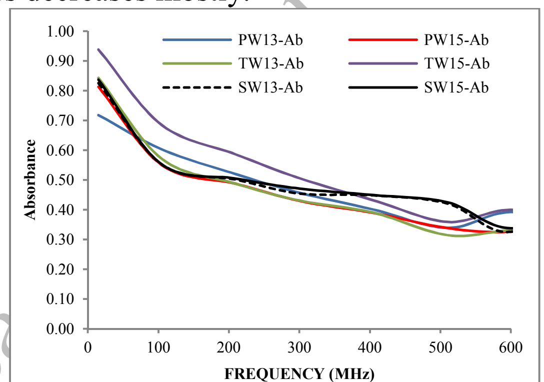


Figure 9: *Absorbance of different woven fabrics with weft density Between 15-600 MHz.*

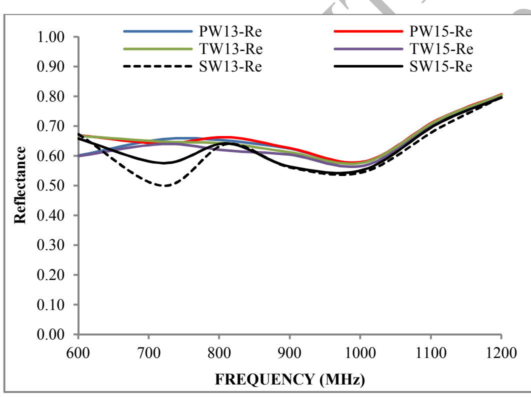


Figure 10: *Reflectance of different woven fabrics with weft density Between 600-1200 MHz.*

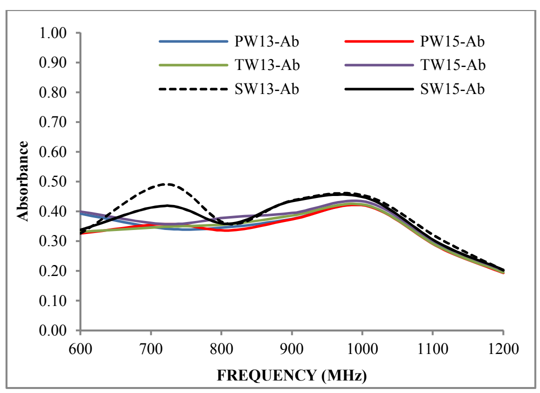


Figure 11: *Absorbance of different woven fabrics with weft density Between 600-1200 MHz.*

The properties of the absorbance and reflectance of the woven fabrics were investigated at medium frequency wave range of 600-1200MHz and the results were shown at Figure 10 and Figure 11. Figures clearly show that, as the frequency increases, there is an increase in reflectance values and there is an decrease in absorbance. The reflectance value at the medium frequency range is higher than low frequency range.

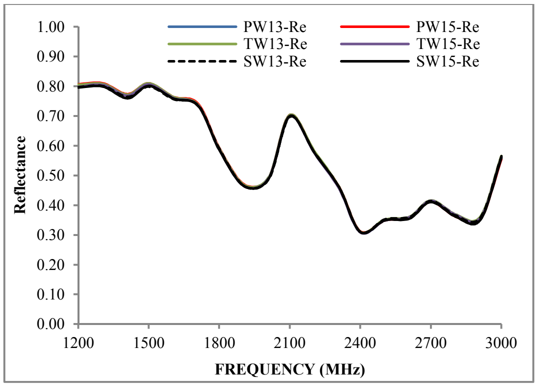


Figure 12: *Reflectance of different woven fabrics with weft density Between 1200-3000 MHz.*

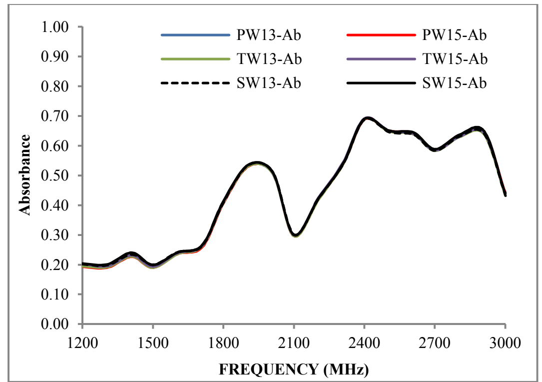


Figure 13: *Absorbance of different woven fabrics with weft density Between 1200-3000 MHz.*

The properties of the Absorbance and Reflectance of the nonwoven fabrics were investigated at higher frequency wave range of 1200-3000MHz and were shown at Figure 12 and Figure 13. It was clearly seen that the reflectance and absorbance curves at the high frequency range is different from that of low and medium frequency range. In the high frequency range, while reflectance curves were at floating mode, the continuously of the curves decrease as a whole were seen.

Electromagnetic Shielding Effectiveness (EMSE) Measurements

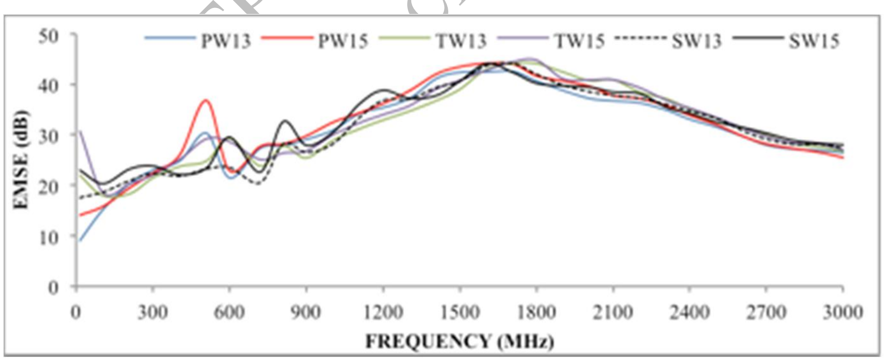


Figure 14: *Electromagnetic Shielding (EMSE) of different woven fabrics with weft density between 15-3000 MHz.*

The figure 14 shows that the best shielding and EMSE results in plain weaves were observed between 1000-2400 MHz. The results clearly indicate 30-45 dB quite high shielding values between 1000-2400 MHz. It is evident that increase in weft density at the plain weaves provide the better shielding. As weft density at the twill weaves increase, until 1800 MHz, It is observed that the shielding and EMSE results increase somewhat. After 1800 MHz, there is no distinction between woven fabrics with different weft density. The highest EMSE result was obtained between 1000-2400 MHz frequencies. It is found that as the increase in weft density at sateen weaves, EMSE results increase until 1000 MHz. After 1000 MHz, as the weft density increase, no important distinction is observed on the EMSE results of the fabrics.

The all woven fabrics were produced at the 13 picks per cm weft density. Effect of different weaves on EMS effectiveness is observed in figure 14. As you see, the weaves change the EMS effectiveness results change too. The best EMS effectiveness results is observed first sateen weaves and then twill and plain weaves. Hence, as the interlacing of the warp and weft yarns decrease, the best shielding is obtained.

The all woven fabrics were produced at the 15 picks per cm weft density. The best shielding between 15-1800 MHz were observed at the plain, sateen and twill weaves respectively. The best shielding between 1800-3000 MHz were found at twill, sateen and plain weaves respectively. Hence, plain weaves at low frequencies and twill weaves at higher frequencies have obtained the best EMS effectiveness results and the best shielding.

4. CONCLUSIONS

In this study, electromagnetic shielding effectiveness of the the woven fabrics produced by considering three different weaves and two different weft density were tested and results were commented.

- ✓ The best shielding values (EMS Effectiveness results) of the woven fabrics produced were obtained between 1000-2400 MHz frequencies.
- ✓ 1000-2400 MHz frequency range is used for mobile phone, wireless technology and 3G technology and the frequency range describe high shielding.
- ✓ Weft density has significant effect on electromagnetic shielding effectiveness. EMS effectiveness also increases with the increase in the weft density of the woven fabrics.
- ✓ Type of the weaves has also significant effect on electromagnetic shielding effectiveness. The best shielding were obtained at sateen weaves. As the interlacing of the warps and weft yarns decrease as the sateen weaves, the best shielding were observed. As the porosity in the woven fabrics decrease, the electromagnetic shielding effectiveness (EMSE values) increases.
- ✓ It is essential that the woven fabrics by varying more types of weaves and weft density should be produced and electromagnetic shielding effectiveness of the fabrics should be investigated.

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