DEVELOPING KNITTED FABRICS WITH ELECTROMAGNETIC SHIELDING PROPERTIES

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Abstract - This study investigates the influence of conductive yarn content on the electromagnetic shielding effectiveness (EMSE) and surface resistivity of knitted fabrics. The fabrics, made with conductive core-spun yarns and 100% cotton yarns, were produced using consistent knitting pattern types and yarn counts, allowing for a comparative analysis of the impact of conductive material quantity. Results indicate a clear inverse relationship between surface resistivity and conductivity, with fabrics containing higher amounts of conductive yarn demonstrating lower surface resistivity and superior shielding performance. Notably, fabrics coded S10-46, S20-46, R10-45, R20-45, I10-49, and I20-49 exhibited significantly better EMSE, particularly in the 0.1-0.6 GHz frequency range, where they performed better than their counterparts. However, a gradual decline in EMSE was observed at higher frequencies, suggesting that metal conductive wires are more effective at shielding electromagnetic radiation at lower frequencies. The shielding mechanisms of absorption and reflection were also evaluated, with absorption consistently surpassing reflection across all fabric types in the 0.1-3 GHz range. These findings highlight the critical role of conductive material quantity and fabric structure in optimizing EMSE for applications in electromagnetic radiation shielding.

Keywords - Electromagnetic Shielding, Knitting, Fabric, Cotton, Conductivity, Stainless Steel, Ring Spinning.

I. INTRODUCTION

In recent years, technological advancements have significantly altered people's habits, making electrical and electronic devices essential in daily life. These technologies, used extensively in homes and workplaces, include mobile phones, wireless networks, computers, medical devices, power lines, and communication systems such as radios and televisions. However, these devices emit significant amounts of electromagnetic (EM) waves, increasing exposure to electromagnetic pollution [1-3]. As a result, EM radiation has become one of the most prominent sources of pollution, ranking just behind noise, air, and water pollution [4, 5].

EM waves consist of electric and magnetic fields, characterized by three key properties: wavelength, frequency, and energy. Wavelength refers to the distance between two wave peaks, measured in meters, while frequency is the number of oscillations per second, measured in Hertz (Hz). Wavelength and frequency are inversely related, meaning that as the wavelength increases, the frequency decreases. The energy carried by a photon in the wave is directly proportional to its wavelength, with shorter wavelengths carrying higher energy [3, 6].

Numerous studies have examined the harmful effects of EM radiation on the human body, exploring its impact on nerve cells, brain tissue, DNA, reproductive systems, immunity, and metabolism [7-9]. Research has shown that EM waves can cause molecular vibrations in biological cells, leading to increased heat and halting DNA and RNA cell repair. There is also evidence suggesting that EM radiation may promote abnormal chemical reactions in the body, potentially triggering the development of cancer, including leukemia. Additionally, exposure to EM waves has been linked to symptoms such as headaches, fatigue, dizziness, sleep disturbances, and memory problems [10, 11].

To mitigate the risks of EM radiation, "shielding" is considered the most effective solution. This involves using conductive or magnetic materials to block or reduce electromagnetic fields [12]. While metals are highly effective at shielding, they tend to be expensive, heavy, and prone to issues like oxidation and corrosion [13]. As an alternative, conductive textiles—fabric materials woven with metallic particles, carbon fibers, or metal wires—offer a lightweight, flexible, and cost-effective solution for EM shielding. These textiles are increasingly used in industries like defense and electronics [3, 14]. Several studies have explored the electromagnetic shielding effectiveness (EMSE) of various textile materials, including woven fabrics, fabric-reinforced composites, and nonwoven surfaces [13, 15-18].

The primary goal of the current research is to develop innovative conductive yarn structures for creating knitted garments with EM shielding properties. This involves wrapping stainless steel fibers with short cotton fibers using a specialized technique in a ring spinning machine. The resulting materials are then used to produce different knitted fabric structures, such as single jersey, rib (1x1), and interlock fabrics, and their mechanical, thermal, and EMSE properties are evaluated.

II. MATERIALS AND METHODS

A. Preparation of Conductive Core-Spun Yarns

In the present study, 100% stainless-steel wire (Elektrisola, Germany) with a 40 µm diameter was used as the conductive core material. The core-spun yarn, which combines stainless-steel (SS) wire and 100% cotton, was produced on a ring spinning machine. The SS wire was carefully positioned at the center of the final core-spun yarn using elastane feeding guides on the spinning machine.

During the production process, the stainless-steel (SS) wire is wrapped with carded cotton roving (Ne1). The cotton fibers are first thinned to the desired thickness in the drafting zone of the machine before they undergo the spinning process. The SS wire is then inserted into the cotton fibers on the exit cylinder, allowing the wire to be incorporated directly into the cotton without any tension or drawing (see Figure 1). Ultimately, two yarn counts (~Ne10 and ~Ne20) were produced with a twist level of αe:4.8 and a spindle speed of 7000 turnings per minute (t/m). The physical properties of the resulting conductive core-spun yarns, along with the corresponding 100% cotton yarns used in knitting, are presented in Table I.

	Yarn count (Ne)		
Yarns types		sd	CV (%)
Core-spun 1	20,15	0,12	0,59
100% cotton	19,12	0,22	1,14
Core-spun 2	9,56	0,05	0,53
100% cotton	10,8	0,33	1,1

Table I. Linear densities (Ne) and evenness values of the ring-spun yarns.

B. Production of Conducted Weft Knitted Fabrics

Different types of weft-knitted fabrics, including single jersey, rib (1x1), and interlock, were created using conductive core-spun yarns and 100% cotton yarns on a 7G automatic flat knitting machine (CMS 420, Stoll). Three distinct course densities were selected for each fabric type during the knitting process. Both the conductive core-spun and cotton yarns were fed through the same carrier on the machine. The structural properties of the resulting knitted fabrics are presented in Tables II, III, and IV, respectively.

Fabric Code	Core Spun Yarn	100% cotton yarn	Loop length (cm)	Courses (per cm)	Wales (per cm)	Amount of conductive yarn (cm/cm²)	Fabric thickness (mm)	Fabric weight (g/m²)
S-10-32	Ne10/1	Ne10/1	0,9	7	5	32	1,72	352
S-10-43	Ne10/1	Ne10/1	0,8	9	6	43	1,53	373
S-10-46	Ne10/1	Ne10/1	0,7	11	6	46	1,43	440
S-20-32	Ne20/1	3x(Ne20/1)	0,9	7	5	32	1,59	356
S-20-43	Ne20/1	3x(Ne20/1)	0,8	9	6	43	1,5	390
S-20-46	Ne20/1	3x(Ne20/1)	0,7	11	6	46	1,38	453

S-10-32= S: Single jersey (knitting type), 10: Yarn count (Ne), 32: Amount of conductive yarn (cm/cm²)

Table II. Structural properties of single jersey knitted fabrics.

Fabric Code	Core Spun Yarn	100% cotton yarn	Loop length (cm)	Courses (per cm)	Wales (per cm)	Amount of conductive yarn (cm/cm²)	Fabric thickness (mm)	Fabric weight (g/m²)
R-10-33	Ne10/1	Ne10/1	1,1	5	3	33	2,11	347
R-10-43	Ne10/1	Ne10/1	0,9	6	4	43	2,37	437
R-10-45	Ne10/1	Ne10/1	0,8	7	4	45	2,41	518
R-20-33	Ne20/1	3x(Ne20/1)	1,1	5	3	33	1,89	348
R-20-43	Ne20/1	3x(Ne20/1)	0,9	6	4	43	2,3	415
R-20-45	Ne20/1	3x(Ne20/1)	0,8	7	4	45	2,46	508

R-10-33= R: Rib (knitting type), 10: Yarn count (Ne), 33: Amount of conductive yarn (cm/cm²)

Table III. Structural properties of rib (1x1) knitted fabrics.

Fabric Code	Core Spun Yarn	100% cotton yarn	Loop length (cm)	Courses (per cm)	Wales (per cm)	Amount of conductive yarn (cm/cm²)	Fabric thickness (mm)	Fabric weight (g/m²)
I-10-36	Ne10/1	Ne10/1	0,9	5	4	36	2,65	578
I-10-48	Ne10/1	Ne10/1	0,8	6	5	48	3,15	666
I-10-49	Ne10/1	Ne10/1	0,7	7	5	49	3,07	722
I-20-36	Ne20/1	3x(Ne20/1)	0,9	5	4	36	3,12	581
I-20-48	Ne20/1	3x(Ne20/1)	0,8	6	5	48	3,14	664
I-20-49	Ne20/1	3x(Ne20/1)	0,7	7	5	49	3,08	693

I-10-36= I: Interlock (knitting type), 10: Yarn count (Ne), 36: Amount of conductive yarn (cm/cm²)

Table IV. Structural properties of interlock knitted fabrics.

C. Measurement of Electromagnetic Shielding Effectiveness (EMSE)

The knitted fabrics were conditioned at 20±2 ºC and 65±2% relative humidity for 24 hours before the experiments. EMSE of the specimens were measured according to ASTM D4935-10 standard by utilizing coaxial transmission line technique in the frequency range between 0,1 GHz and 3 GHz. A compact testing device (Electro-Metrics Inc., model EM-2107 A, USA) was used to determine the EMSE of the knitted fabrics. Reflectivity, absorption, and transmissibility of the electromagnetic (EM) wave power of the textiles were assessed via a network analyzer (Rohde & Schwarz, ZVL/9 kHz-13.6 GHz) equipped with two coaxial connectors and two attenuators (10 dB) for generating and receiving EM signals.

To realize the EMSE assessment of knitted fabrics in accordance with insertion-loss method, two specimens were required for each test; one for the reference and another for the loaded samples (conductive knitted fabrics; single jersey, rib (1x1), and interlock). The specimen dimension was set to be 133 mm, which matches the exact diameter as the outer ring dimension. Considering incident and transmitted power, the difference in attenuation between a reference sample and the loaded specimen was evaluated to determine

EMSE. The results of the calculations were expressed in decibels (dB) which is the unit indicating the power ratio that is used for specifying the shielding efficiency.

Surface resistivity of the knitted fabrics was determined by utilizing the Keithley 6517A Electrometer/High Resistance Meter device in accordance with the ASTM D257-07 standard. Surface resistivity was assessed by putting a voltage potential across the specimen's outer layer, measuring the resulting current.

III. RESULTS AND DISCUSSION

A. The Impact of Conductive Material Amount on EMSE and Surface Resistivity

To evaluate the impact of conductive yarn quantity on the electromagnetic shielding effectiveness (EMSE) and surface resistivity of knitted fabrics, the knitting pattern type and yarn count were kept consistent across samples. As a result, fabrics with the same pattern and yarn count were compared to each other (Fig. 1-5). It is well-established that surface resistivity and conductivity are inversely related, meaning lower surface resistivity indicates higher conductivity. Additionally, the amount of conductive yarn per square inch varied depending on the total length of the loops in the knitted structure [19]. The data clearly showed that fabrics coded S10-46, S20-46, R10-45, R20-45, I10-49, and I20-49 exhibited lower surface resistivity within their respective categories due to the higher amount of conductive material per unit area. Regarding EMSE performance, these same fabrics (S10-46, S20-46, R10-45, R20-45, I10-49, and I20-49) demonstrated superior shielding effectiveness compared to other fabrics in the same group, which can be attributed to their higher conductivity.

Furthermore, all knitted samples showed better EMSE in the 0.1-0.6 GHz frequency range, with a gradual decline in performance observed at higher frequencies, despite some fluctuations. This decrease in EMSE at higher frequencies may be due to the metal conductive wires being more effective at shielding electromagnetic radiation at lower frequencies than at higher ones [20].

The shielding of electromagnetic waves involves two main mechanisms: absorption and reflection. The absorption and reflection characteristics of the knitted fabrics are shown in (Fig. 1-6). Both reflection and absorption decreased as the frequency increased. Additionally, absorption levels were consistently higher than reflection values across all groups in the 0.1 GHz to 3 GHz range, which can be attributed to the inherent properties of the conductive material [21].

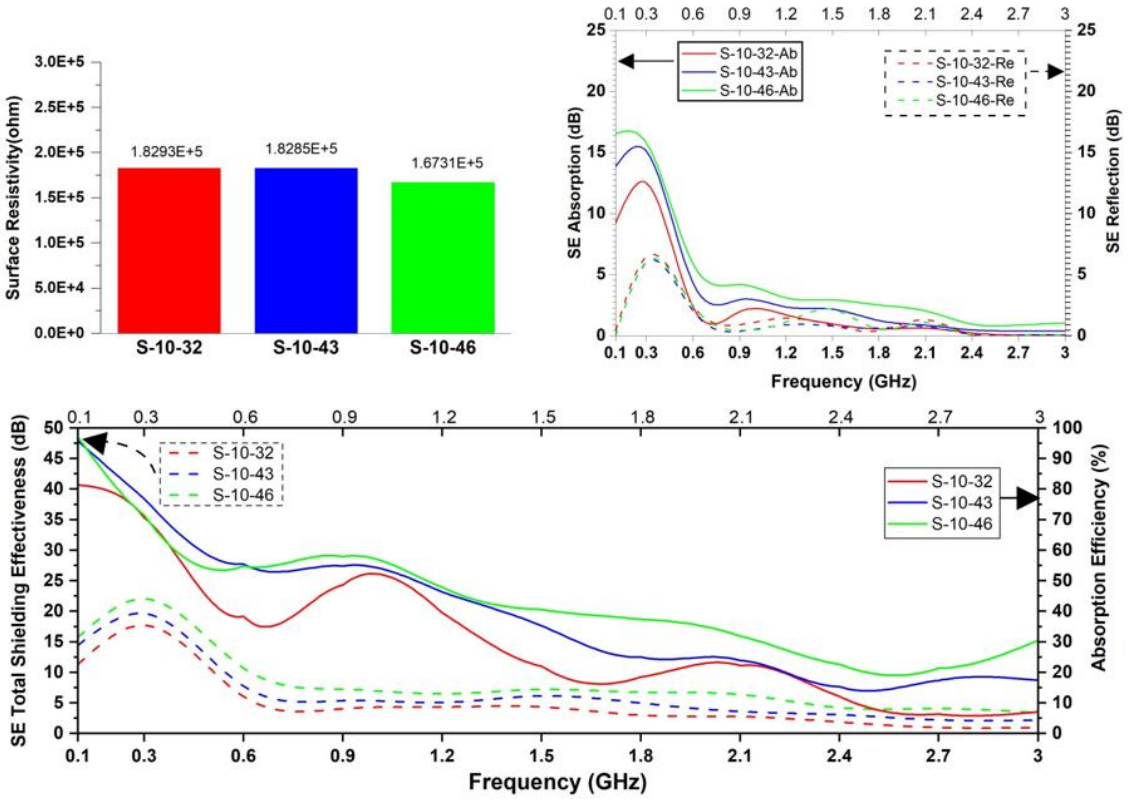


Fig. 1. The influence of conductive material on EMSE performance of single jersey fabrics made of Ne10 conductive yarn.

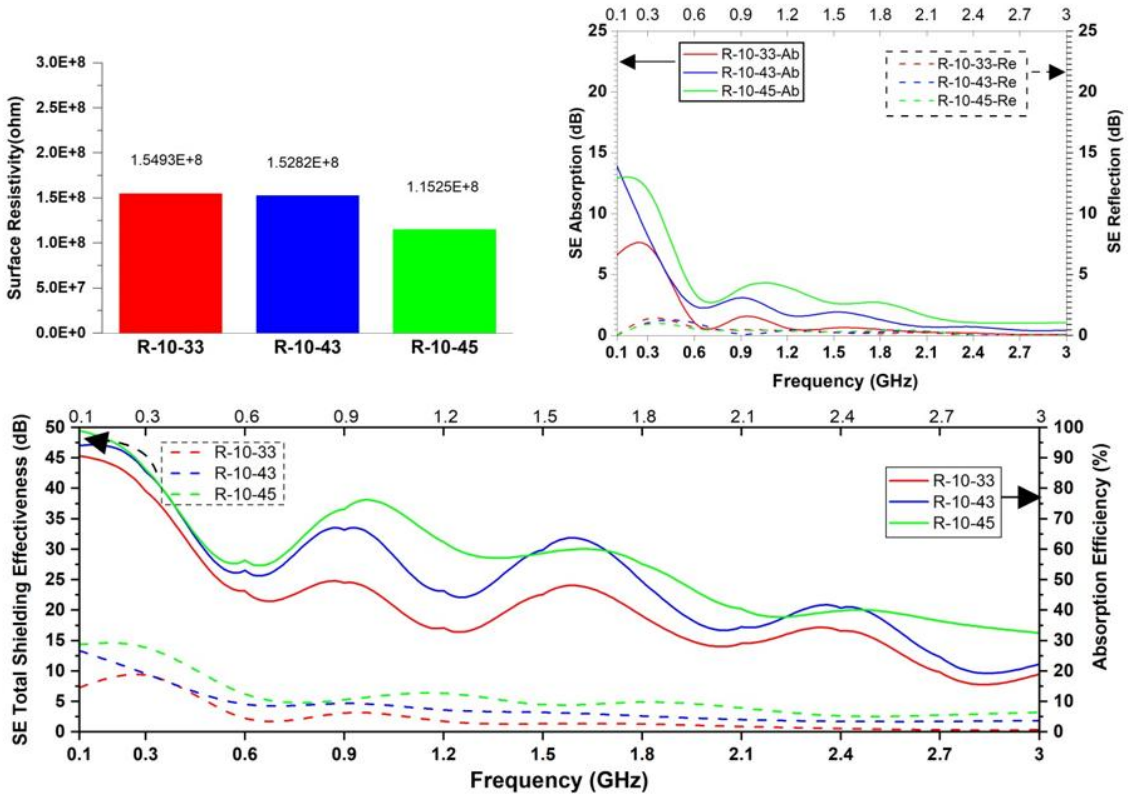


Fig. 2. The influence of conductive material on EMSE performance of ribana fabrics made of Ne10 conductive yarn.

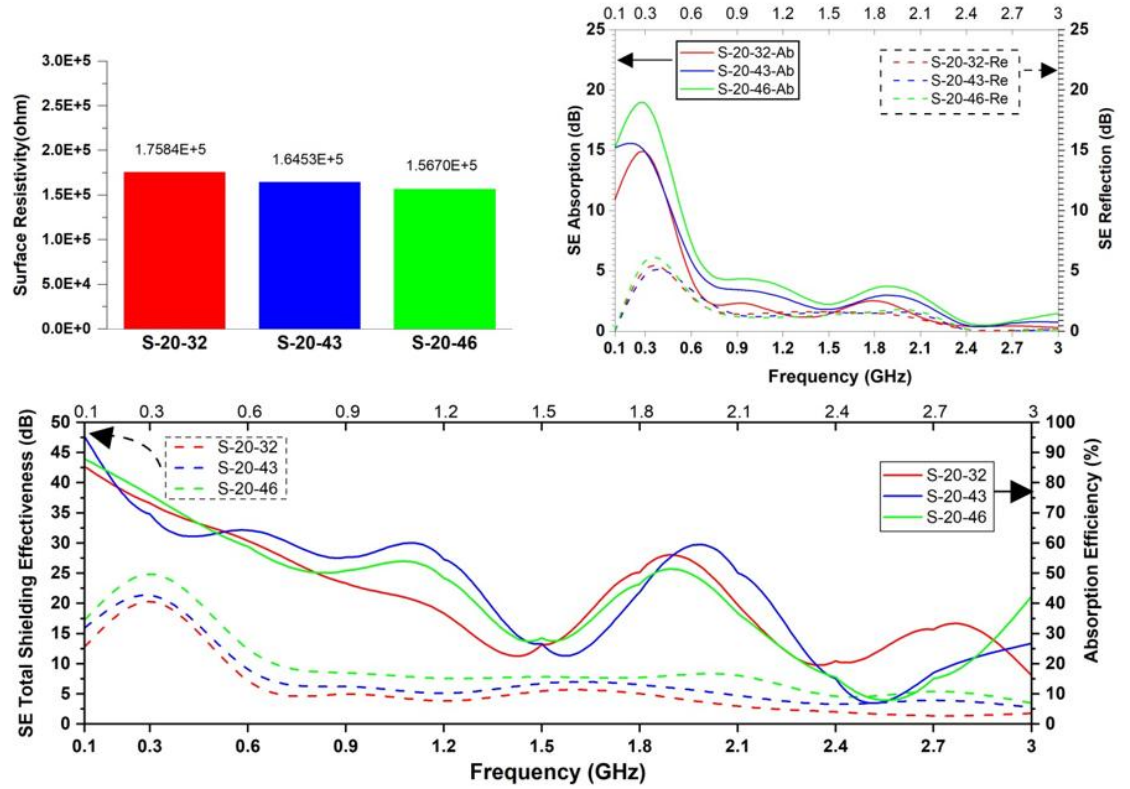


Fig. 3. The influence of conductive material on EMSE performance of single jersey fabrics made of Ne20 conductive yarn.

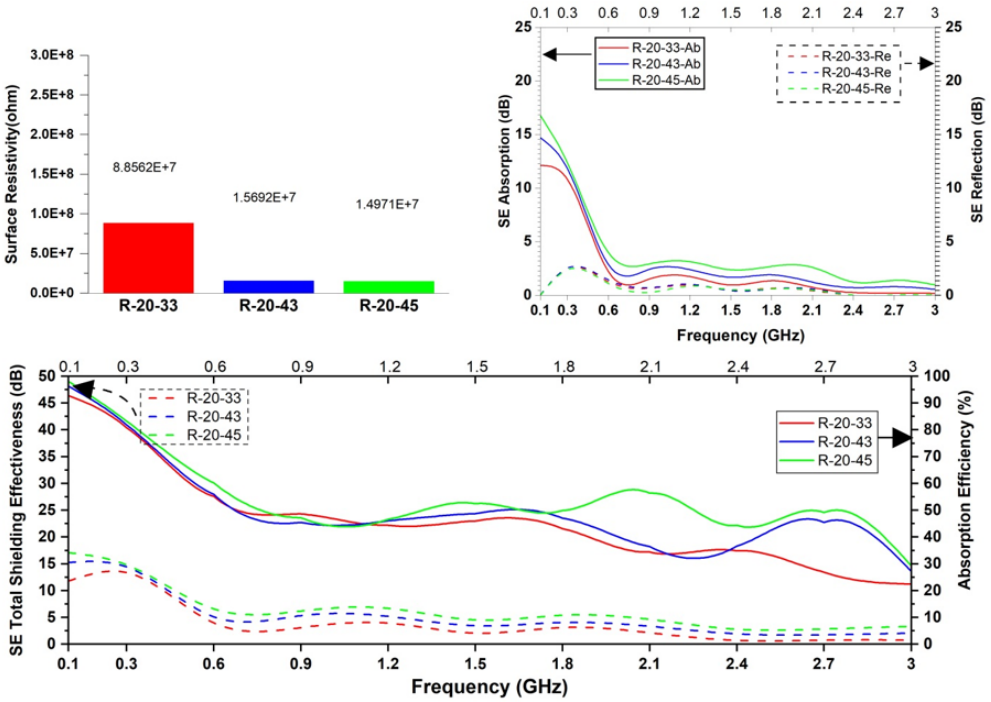


Fig. 4. The influence of conductive material on EMSE performance of ribana fabrics made of Ne20 conductive yarn.

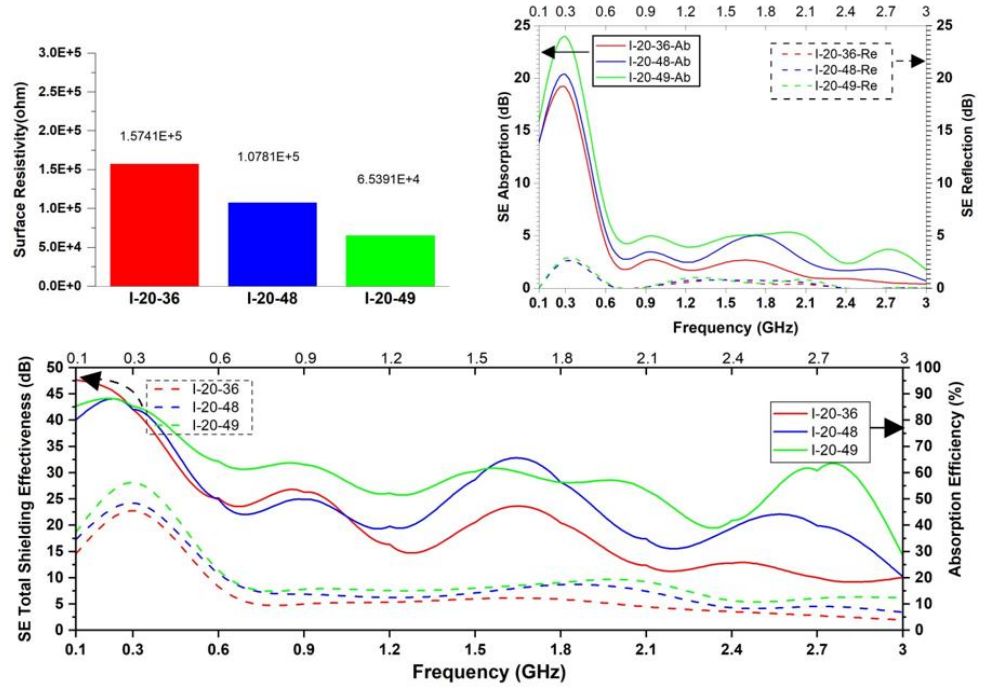


Fig. 5. The influence of conductive material on EMSE performance of interlock fabrics made of Ne20 conductive yarn.

IV. CONCLUSION

This study demonstrates that the amount of conductive yarn incorporated into knitted fabrics plays a significant role in determining both the electromagnetic shielding effectiveness (EMSE) and surface resistivity. Fabrics with higher conductive yarn content exhibited lower surface resistivity and superior EMSE, particularly in the lower frequency range of 0.1-0.6 GHz. The inverse relationship between surface resistivity and conductivity underscores the importance of material composition in achieving optimal shielding performance. Furthermore, the study highlights the effectiveness of metal conductive wires in shielding electromagnetic radiation, with better performance at lower frequencies and a gradual decline at higher frequencies. The analysis of absorption and reflection behaviors further confirms that absorption is the dominant shielding mechanism in the 0.1-3 GHz range. These findings suggest that the design of knitted fabrics for electromagnetic radiation shielding

should prioritize increasing the conductive material content while considering frequency-dependent shielding behaviors. Overall, the results contribute valuable insights into the development of knitted textiles for use in applications requiring effective electromagnetic protection.

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