Investigation of the technical and physical properties of metal composite 1×1 rib knitted fabrics

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ABSTRACT – REZUMAT

Investigation of the technical and physical properties of metal composite 1x1 rib knitted fabrics

In this study, it was aimed to determine electromagnetic shielding effectiveness, antibacterial activity, surface resistivity and bending rigidity properties of 1×1 rib knitted fabrics. For this purpose, copper (Cu), stainless steel (SS) and silver (Ag) wires were commingled with two nylon filaments to produce metal composite yarns. 1×1 rib fabrics were produced by these composite yarns. Electromagnetic shielding effectiveness (EMSE), antibacterial activity, surface resistivity and bending rigidity of the composite knits were measured. Electromagnetic shielding measurements of samples were conducted between 1.0–5.0 GHz frequency. Antibacterial activity test was applied according to AATCC 100 standard against K. pneumoniae and S. aureus bacteria. Results showed that knitted fabrics generally have lower SE values than 10 dB at wale direction. The double layer samples provide higher EMSE than single layer samples for all metal types. Maximum EMSE value was obtained as 57.12 dB. The use of metal wire significantly reduced surface resistivity of knitted fabrics. Copper composite knitted fabrics showed 99 % antibacterial activity against both bacterial species. When compared to the control sample, the use of metal wire significantly increased the rigidity of the samples.

Keywords: *composite yarns, composite fabric, knitted fabric, physical properties, technical properties*

Analiza proprietăților tehnice și fizice ale compozite metalice din tricot patent 1x1

În acest studiu, s-a urmărit determinarea eficacității ecranării electromagnetice, a activității antibacteriene, a rezistivității la suprafață și a proprietăților de rigiditate la încovoiere a tricotului patent 1×1. În acest scop, fire de cupru (Cu), oțel inoxidabil (SS) și argint (Ag) au fost combinate cu două filamente de nailon pentru a produce fire compozite metalice. Tricoturile patent 1×1 au fost produse utilizând aceste fire compozite. Ulterior, au fost determinate eficacitatea ecranării electromagnetice (EMSE), activitatea antibacteriană, rezistivitatea la suprafață și rigiditatea la încovoiere a tricoturilor compozite. Măsurătorile de ecranare electromagnetică ale probelor au fost efectuate la o frecvență de 1,0–5,0 GHz. Testul de activitate antibacteriană a fost aplicat conform standardului AATCC 100 față de bacteriile K. pneumoniae și S. aureus. Rezultatele au arătat că tricoturile prezintă, în general, valori ale ecranării elecromagnetice mai mici de 10 dB în direcția şirului de ochiuri. Probele cu dublu strat asigură valori EMSE mai mari decât probele cu un singur strat pentru toate tipurile de metale. Valoarea maximă EMSE obținută a fost de 57,12 dB. Utilizarea firului metalic a redus semnificativ rezistivitatea la suprafață a tricoturilor. Materialele tricotate din compozit de cupru au prezentat 99% activitate antibacteriană pentru ambele specii bacteriene. În comparație cu proba martor, utilizarea firului metalic a crescut semnificativ rigiditatea probelor.

Cuvinte-cheie: *fire compozite, material compozit, material tricotat, proprietăți fizice, proprietăți tehnice*

INTRODUCTION

Electromagnetic (EM) shielding is becoming an increasingly important feature in industrial applications, secret and shielded rooms, wall covering, healthcare products, protective clothing, military tents and worker clothes. Fabrics containing conductive metal wires are one of the widely used materials for EM shielding. These materials have shown rapid developments with increasing interest in recent years. In many studies in the literature, it has been investigated the importance of knitting structure, density, weight, thickness, tightness, machine gauges, yarn and conductive material types on the electromagnetic shielding effectiveness (EMSE) of the knitted fabrics [1–11].

Perumalraj and Dasaradan (2009), Ortlek et al. (2011), Çeken et al. (2011) and Abdulla et al. (2017) have been widely investigated the effect of knitting geometry to EMSE. Different types of knitted structures producing with the same yarns affected EMSE values because of length and position of float, tuck and loop in the knit fabric structure [6, 9]. For the production of knitted fabric containing metal wires, researchers preferred different methods such as flat [3], circular [4] and warp knitting machines [8]. In these machines, the effects of different machine gauge and tightness factor on EMSE were analyzed [10]. Ring core [1, 7, 9], siro core [2], plied [3, 5], hollow spindle [4, 8, 11], Dref [12] and commingled [13–16] composite yarns containing metal wires or metal wires as direct [3] were used during knitting process in the literature. Previous research findings have reported that EMSE decreases with the increase of frequency. Also fabrics having denser conductive materials give higher shielding results depending on the measurement direction [4, 9]. Moreover, these knitted fabrics including metal wires were laminated or used as a component of the composite structure. Generally, lamination, composites and multilayer fabrics show a higher EMSE values than knitted fabrics. Furthermore, an increase in angle and number of layers provide positive impact on the EMSE [7–8, 11–12]. Yu et al. (2015) found that the structures at 90° intervals showed a better EMSE values compared to those at 0° and 45° intervals [8].

The aim of this research is to determine the physical and technical properties of knitted fabrics containing metal composite yarn. In this context, composite yarns were produced with the commingling principle instead of other mentioned conventional techniques. Stainless steel, copper, silver wires and two polyamide 6.6 filaments was combined in intermingling machine. Obtained yarns were knitted in flat knitting machine. Antibacterial activity, surface resistivity and electromagnetic shielding effectiveness of sample were tested as technical properties. Bending rigidity was also measured as physical property. Results were analyzed statistically.

MATERIAL AND METHOD

Production of composite yarn and knitted fabric samples

In the study, 3-component metal composite yarns were produced by commingling technique. Metal wire was centered between two polyamide yarns to prevent the breaking of metal wires by the effect of compressed air (figure 1).

Copper (Cu), stainless steel (SS) and silver (Ag) wires were commingled with polyamide yarns at 5 bar pressure and 150 m/min production speed. Properties of filaments and composite yarns are given in table 1.

Table 1

TECHNICAL PROPERTIES OF FILAMENTS AND COMPOSITE YARNS	
Filaments	**Technical Properties**
Polyamide 6.6 (PA)	78 denier/68 filaments
Silver Monofilament (Ag) (Isolated)	107 denier (47 μ diameter)
Copper Monofilament (Cu)	157 denier (50 μ diameter)
Stainless Steel Monofilament (SS)	144 denier (50 μ diameter)
Composite Yarns	
PA + SS + PA (PSSP)	222 denier/137 filaments
PA + Ag + PA (PAgP)	261 denier/137 filaments
PA + Cu + PA (PCuP)	306 denier/137 filaments

Microscope images of composite yarns were taken at 20× magnification ratio by digital camera microscope (figure 2).

Stainless steel, copper and silver composite yarns were knitted to 1×1 Rib fabrics with same parameters by Shima Seiki SFF152 flat knitting machine. In order to increase the EMSE by considering the results of the previous studies [17–18], double layer samples were produced by sewing. The properties of composite fabrics are given in table 2.

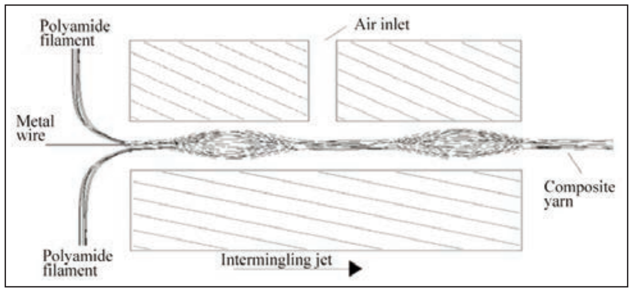


Fig. 1. The 3-component commingling process

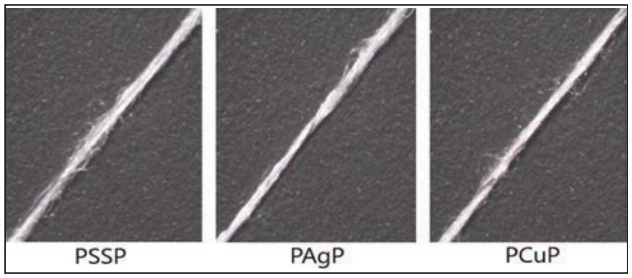


Fig. 2. Microscope images of different types of composite yarns (20×)

Table 2

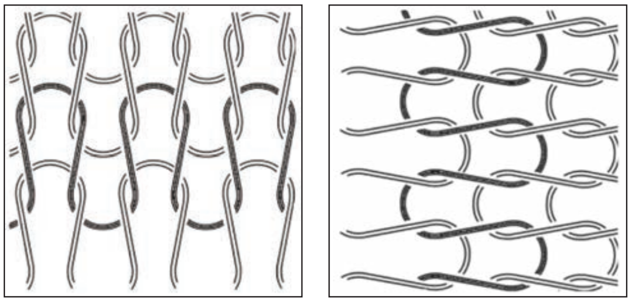
PROPERTIES OF COMPOSITE FABRICS				
Sample codes*	**Yarn type**	**Course/cm**	**Wale/cm**	**Weight (g/m²)**
Control	PA	12	14	249.00
CuS	PCuP	12	11	377.50
SS	PSSP	11	12	278.30
AgS	PAgP	12	11	326.00

* The last letter of sample code was used as D for double layer samples (ex. CuD)

Measurement of electromagnetic properties

The reflection (S11/S22) and transmission (S21/S12) coefficients of knitted fabrics were measured according to free space test method by using Agilent PNA-L model network analyzer with the range of 1.0–5.0 GHz. The measurement system was calibrated with the keysight (Agilent) 85056A mechanical calibration kit. In the free space method, measurements can be performed in the usage area of the product. This method is almost non-limiting in terms of sample sizes and types and allowing for a wide frequency range [19–20]. In measuring process, single and double layer samples were placed between two horn antennas at course (figure 3, *a*) and wale (figure 3, *b*) directions by rotating clockwise 90°. In addition to EMSE, absorbed and reflected power ratios were also examined.

The measured S parameters (S11/S22 and S12/S21) were used for EMSE characterization. EMSE is defined as logarithmic form of the ratio between the field or power intensity with (E_T) and without (E_0)



a b

Fig. 3. Placements of sample at: *a* – wale direction; *b* – course direction

shielding material. SE values can be calculated as dB by the following Equation 1 [21–22]:

$$SE = 20 \log \left| \frac{E_0}{E_T} \right| = 20 \log \left| \frac{H_0}{H_T} \right| = 10 \log \left| \frac{P_0}{P_T} \right| \quad (1)$$

The transmitted power (*T*), reflected power (*R*) and absorbed power (*A*) were calculated by using Equations 2, 3 and 4 [23].

$$T = \left| \frac{\text{Transmitted electric field}}{\text{Incident electric field}} \right|^2 = \left| \frac{E_T}{E_i} \right|^2 = \\ = |S_{12}|^2 = |S_{21}|^2 \quad (2)$$

$$R = \left| \frac{\text{Reflected electric field}}{\text{Incident electric field}} \right|^2 = \left| \frac{E_R}{E_i} \right|^2 = \\ = |S_{11}|^2 = |S_{22}|^2 \quad (3)$$

$$A = 1 - (T + R) \quad (4)$$

Especially, the reflectivity of the electromagnetic shield causes secondary interference [24]. Moreover, absorbability of material helps to reduce the visibility on radar [25]. Therefore, it is more meaningful to examine these components separately when defining electromagnetic characterization of materials. Obtained data were analyzed statistically in four different frequency ranges as 1–2, 2–3, 3–4 and 4–5 GHz. These frequencies are in the class D, E, F, G of U.S. military microwave bands [26].

Measurement of surface resistivity

Conductivity of the knitted fabric was measured by using ELME MULTIMEG megohmmeter at 55.0% relative humidity (RH) and 20.0°C. Surface resistivity test was carried out according to "TS EN 1149-1: Electrostatic properties – Part 1: surface resistivity" standard. The measurements were repeated 10 times for each sample in wale and course directions. The classification of samples was carried out according to their resistivity (ohm/sq) as given in table 3 [27].

Table 3

SURFACE RESISTIVITY CLASSIFICATION OF MATERIALS

Classification	Surface resistivity (ohm/sq)
Conductive	$<10^5$
Dissipative	10^5 to 10^{12}
Insulating	$>10^{12}$

Antibacterial activity test

Antibacterial activity tests were performed according to AATCC 100 standard. AATCC 100 is a quantitative method for the determination of antibacterial activity of textile materials. *K. pneumoniae* and *S. aureus* which causes various infections in humans were chosen as test bacteria to investigate the antibacterial properties of knitted fabric samples.

Bending rigidity test

The bending rigidity test provides information about softness of fabric. Thus, bending rigidity of the knitted fabrics was tested to determine the effect of the metal wire on the softness of fabrics. The test was conducted according to ASTM D 4032 standard. Tests were repeated 5 times for each sample by using a digital pneumatic stiffness tester. Obtained data were analyzed statistically.

RESULTS AND DISCUSSION

General evaluation for 1–5 GHz frequency range

The weft knitting structure and the contact points of loops were examined together for describing the EMSE behaviors at different directions in detail. In weft knitting, the loops are formed in the course direction. So, the conductive wire shows continuity along the course direction of fabric, whereas, the conductivity in the wale direction only occurs with the contact of metal wires at the connection points of the loops. Thus, the conductivity is interrupted in the wale direction. In previous studies it was noted that the orientation of the conductive yarns has an important effect on the EMSE and weft knitted fabrics have EMSE ability in their course direction [28–30]. In our study, all knitted samples showed lower EMSE than 10 dB for wale direction in accordance with previous studies. Maximum EMSE values were determined as 57.12 (CuD), 54.27 (AgD) and 48.73 (SD) in the course direction of double layer samples. EMSE, absorbed and reflected power ratio of single and double layer knitted fabrics at course direction are given in figure 4.

In first step, the entire data set was subjected to statistical analysis for general evaluation. Normality of data was examined with Kolmogorov-Smirnov test. Data was not distributed normally with p values less than 0.05. Kruskal-Wallis and Mann-Whitney U, which are distribution free and rank-based nonparametric tests, were applied to determine the difference between groups and with-in-group respectively [31–32]. Results are given in table 4.

According to result, the difference in the number of layer did not cause a significant change in the absorbed and reflected power ratio ($p > 0.05$). But, double layer samples provided significantly higher EMSE then single layer samples in the 1–5 GHz frequency range ($p < 0.05$). Similar to our results, Chen et al. determined that the EMSE increases as fabric thickness increases and the tendency of EMSE keeps the similar shielding effectiveness at various frequencies. Also they noted that the protective activity of a

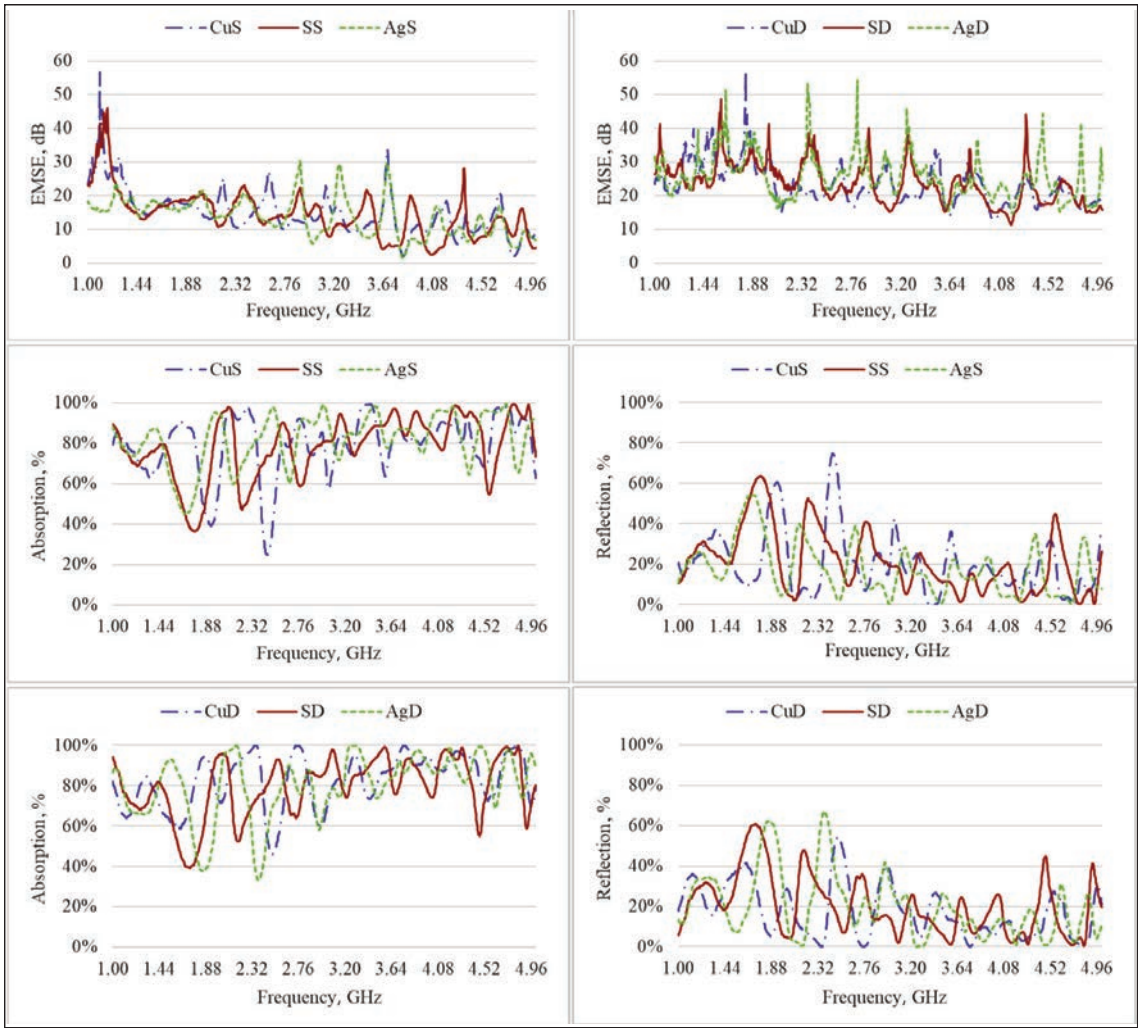


Fig. 4. EMSE, absorbed and reflected power ratio of single and double layer knitted fabrics

Table 4

KRUSKAL-WALLIS AND *MANN-WHITNEY U TESTS STATISTICS OF METAL TYPES							
Material type		**Single layer**			**Double layer**		
		EMSE	**Absorbed power ratio**	**Reflected power ratio**	**EMSE**	**Absorbed power ratio**	**Reflected power ratio**
Mean ranks	SS	**1388.51**	1248.05	**1587.77**	1326.31	**1289.58**	**1562.85**
	Cu	**1405.53**	**1442.02**	**1550.81**	1225.65	1478.41	1424.74
	Ag	1306.96	**1410.93**	962.42	1549.04	**1333.02**	1113.41
Asymp. Sig.		0.017	0.000	0.000	0.000	0.000	0.000

* Groups with no statistically significant difference were marked in bold.

single layer is unsatisfactory for general applications, but multilayer fabrics can provide adequate shielding effectiveness [17].

It can be said that the absorbed and reflected power ratio of different metal types were significantly different. In addition, the results indicated that the metal types had a determinant on the ratio of absorbed/reflected power. Mean ranks showed that the samples containing SS and Cu showed higher EMSE and reflected power ratio than Ag samples for single layer. The change in the number of layers had a different effect on different metal types. The increase in the number of layers was significantly increased the performance of the silver composite sample and these samples showed higher EMSE than SS and Cu samples respectively. The probable cause of the situation was that different types of metals have different absorption/reflection properties.

In figure 4, EMSE showed a decreasing trend with increasing frequency. Hence, spearman's correlation analysis was performed to determine the level and significance of this trend (table 5).

Studies in the literature reported that the reflection loss decreases with increasing frequency oppositely

Table 5

SPEARMAN'S CORRELATION RESULTS			
Correlation coefficients		**Frequency**	
		Single layer	**Double layer**
EMSE	Correlation coefficient	–0.652*	–0.512*
	Sig. (2-tailed)	0.000	0.000
	N	2733	2733
Absorbed power ratio	Correlation coefficient	0.451*	0.445*
	Sig. (2-tailed)	0.000	0.000
	N	2733	2733
Reflected power ratio	Correlation coefficient	–0.241*	–0.254*
	Sig. (2-tailed)	0.000	0.000
	N	2733	2733

* Correlation is significant at the 0.01 level (2-tailed).

the absorption loss [31–32]. Wavelength of incident waves decreases by increasing frequency. So, electromagnetic waves having shorter wavelength can penetrate the gaps of fabrics [33–34]. The significant Spearman correlation coefficient value of –0.652 confirms what was apparent from the graph; there appears to be a strong negative correlation between the EMSE and frequency for single layer samples. There was a moderate level negative correlation (–0.512) for double layer samples. It can be said that the double layer samples provided more stable shielding than single layer against the shorter wavelength. The obtained results were consistent with the literature. In table 5, the closer correlation coefficients indicated that the change in the number of layer did not make a significant difference on the absorbed/reflected power ratio against the frequency. On the other hand, there is a significant correlation between the absorbed power ratio and frequency at moderate level.

Evaluation of EMSE with segmentation of frequency range

Different metal types can show different performance for various frequency ranges. Changing performance in different segments can be overlooked when all data is used. Therefore, in this section, EMSE and absorbed/reflected power ratio of samples were analyzed for 1–2, 2–3, 3–4 and 4–5 GHz frequency ranges separately for making a comprehensive EMSE characterization. Statistical tests results are given in table 6.

According to table 6, in the range of 1–3 GHz, stainless steel had a better EMSE than copper and silver, the performance of copper came into prominence between 3–5 GHz for single layer samples. There was no statistically significant difference among the EMSE values of the double layer samples in the 1–2 GHz range. It was determined that the increase in the number of layers increased the performance of silver composite sample than others. AgD samples showed the best performance especially in the 3–5 GHz range. Reflected power ratio of SS sample is higher than CuS and AgS samples between 1–3 GHz frequency ranges. CuS samples came into prominence with reflected power ratio between 3–5 GHz similarly the EMSE results. AgS sample showed a better absorbed power ratio between 1–3 and 4–5 GHz

Table 6

KRUSKAL-WALLIS AND *MANN-WHITNEY U TESTS STATISTICS FOR METAL TYPES									
Metal type		**Single layer**				**Double layer**			
		1–2 GHz	2–3 GHz	3–4 GHz	4–5 GHz	1–2 GHz	2–3 GHz	3–4 GHz	4–5 GHz
		EMSE							
Mean Ranks	SS	371.90	379.35	339.57	312.42	326.73	399.58	291.18	**278.49**
	Cu	380.14	**301.60**	372.89	**377.02**	359.58	**243.14**	319.59	**311.07**
	Ag	**279.96**	346.55	310.54	333.56	345.69	384.78	**412.23**	**433.44**
Asymp. Sig.		0.000	0.000	0.168	0.002	0.206	0.000	0.000	0.000
		Absorbed power ratio							
Mean Ranks	SS	**285.92**	**278.63**	**334.15**	[a]342.38	**322.94**	328.48	321.00	333.09
	Cu	368.52	365.13	**430.05**	**[a]309.19**	368.98	**379.45**	385.89	353.78
	Ag	377.57	383.74	**258.80**	371.43	340.08	319.57	**316.11**	336.14
Asymp. Sig.		0.000	0.000	0.002	0.003	0.043	0.002	0.000	0.481
		Reflected power ratio							
Mean Ranks	SS	**483.75**	**406.57**	**339.32**	[a]338.97	**467.66**	356.60	365.50	349.42
	Cu	**428.74**	319.30	**454.56**	**[a]372.70**	**430.28**	**305.32**	368.45	327.36
	Ag	**119.51**	301.64	**229.12**	311.33	**134.06**	365.58	**289.05**	346.22
Asymp. Sig.		0.000	0,000	0.002	0.004	0.000	0.002	0.000	0.434

* The group, which is statistically different from the others, was marked in bold.
[a] The difference is not significant.

Table 7

KRUSKAL-WALLIS TEST STATISTICS OF NUMBER OF LAYERS FOR EMSE					
Frequency ranges (GHz)		1–2	2–3	3–4	4–5
Mean ranks	Single layer	422.52	397.09	394.93	372.03
	Double layer	952.48	971.91	968.07	990.97
Asymp. Sig.		0.000	0.000	0.000	0.000

the first and second layers and these waves are mostly absorbed and transformed into heat. Furthermore when waves that reflected from the first layer and second layer are in opposite directions to each other, destructive interference can be occur and create a wave that is weaker than either of them [35–36]. In the research this effect was considered in total absorption. Multilayer structure, which consists of the composite material having higher absorption ability in upper layer and the reflective material for the

Table 8

TESTS STATISTICS OF SPEARMAN'S CORRELATIONS								
Correlation Coefficients	**Single Layer**				**Double Layer**			
	1–2 GHz	2–3 GHz	3–4 GHz	4–5 GHz	1–2 GHz	2–3 GHz	3–4 GHz	4–5 GHz
	EMSE							
Correlation Coff.	–0.306	–0.157	–0.316	–0.103	0.431	0.109	–0.119	0.043
Sig. (2-tailed)	0.000	0.000	0.000	0.007	0.000	0.004	0.002	0.257
	Absorbed power ratio							
Correlation Coff.	–0.316	–0.021	0.235	0.009	-0.190	–0.157	0.218	–0.079
Sig. (2-tailed)	0.000	0.577	0.000	0.810	0.000	0.000	0.000	0.040
	Reflected power ratio							
Correlation Coff.	0.253	0.018	–0.257	–0.014	0.089	0.156	–0.371	0.079
Sig. (2-tailed)	0.000	0.639	0.000	0.721	0.020	0.000	0.000	0.039

ranges. Absorbed power ratio of CuD samples is generally higher than the other samples in the 1–4 GHz ranges. There was no statistically significant difference among the metal types in terms of the absorbed and reflected power ratio values between 4–5 GHz range. Kruskal-Wallis tests results of EMSE for number of layers are given in table 7.

According to table 7, double layer samples showed higher EMSE at statistically significant level than single layer for all segments. Spearman's correlation analysis was conducted to determine correlations between EMSE, absorbed/reflected power ratio and frequency. Test results are given in table 8.

In table 8, EMSE values showed a decreasing tendency with increasing frequency between 1–5 GHz frequencies. In addition, this correlation was at moderate level with –0,652 correlation coefficient. When frequency was examined in segments, it can be said that there is a weaker significant correlation in the same direction for single layer samples. On the other hand, the increase in the number of layer changed the inclination of this trend as positive in the range of 1–3 GHz. It showed that the double layer samples provide better EMSE against increasing frequency. There were generally weak correlations between absorbed/reflected power ratios and frequency.

It can be mentioned the three different shielding mechanisms in double layer structure. In the first mechanism, the waves passing through the first layer are absorbed by the second layer. In the second mechanism, some of the waves reflected from the second layer are absorbed by the first layer. In the third mechanism, repetitive reflections occur between

second layer, can be more effective for reducing the secondary interference considering these mechanisms, the possible design recommendations to reduce the secondary interference for different frequency ranges are given in table 9.

Table 9

STRUCTURE RECOMMENDATIONS TO REDUCE THE SECONDARY INTERFERENCE		
Frequency	**First layer**	**Second layer**
1-2 GHz	Ag or Cu Composites	SS Composite
2-3 GHz	Ag or Cu Composites	SS or Ag Composites
3-4 GHz	Cu Composite	SS or Cu Composites
4-5 GHz	Ag or SS Composites	SS, Cu or Ag Composites

Surface resistivity test results

Surface resistivity of composite and control sample measured at 55 % RH and 20°C conditions. Means of test results are given in table 10.

According to classification in table 10, test results show that 100% polyamide knitted fabric was non-conductive as expected. In addition, the isolation of silver affected the results and the silver composite materials exhibited insulating behavior. On the other hand, copper and stainless steel composite fabrics could be classified as conductive with their very low surface resistivity.

Table 10

SURFACE RESISTIVITY TEST RESULTS		
Sample type	Surface resistivity (ohm/sq)	
	Wale direction	Course direction
Control sample (100% PA)	$> 2\times10^{12}$	$> 2\times10^{12}$
Copper composite	$< 10^{3}$	$< 10^{3}$
Stainless steel composite	$< 10^{3}$	$< 10^{3}$
Silver composite	3.87×10^{9}	$> 2\times10^{12}$

Table 11

BENDING RIGIDITY TEST RESULTS		
Sample type	Means of stiffness (kgf)	CV (%)
Control sample (100% PA)	0.120	1.897
Copper composite	0.305	3.361
Stainless steel composite	0.304	4.563
Silver composite	0.261	9.171

Antibacterial activity test results

Previous studies in the literature mentioned that the elemental silver and stainless steel (AISI 316L) have no antimicrobial properties [37–39]. Thus, antibacterial activity test was only applied to copper composite samples. Test results showed that the copper composite samples showed very high antibacterial activity against *K. pneumoniae* and *S. aureus* bacteria. After 24 hours of incubation time, there was no colony in petri dishes for both bacteria. Petri dishes photos of copper composite sample for 0 (*a*) and 24 (*b*) hours are given in figure 5.

In our copper composite knitted sample, this rate was about 50 % and it provided 99% antibacterial (bactericidal) activity against *K. pneumoniae* and *S. aureus* bacteria (figure 5).

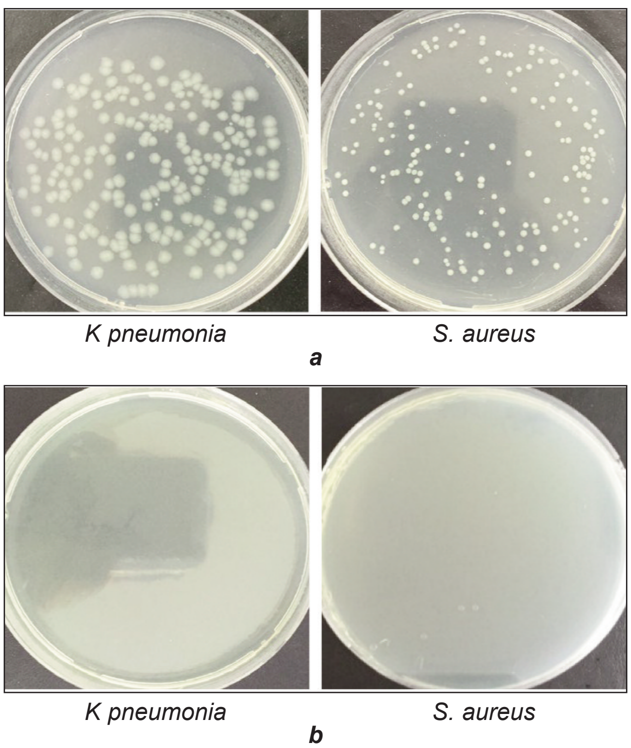


Fig. 5. Petri dishes photos after 0 and 24 hours contact times

Bending rigidity test results

Bending rigidity test was conducted to determine the softness of the composite samples. Results are given in table 11.

Test results were evaluated statistically. Kolmogrov Simirnov and levene tests were applied to determine normality of the data and homogeneity of variance respectively. Analysis showed that the distribution was normal (sig = 0.160) but the variance was not homogeneous (sig. = 0.006). ANOVA and Tamhane multiple comparison test were applied to data. According to ANOVA, difference between the groups was statistically significant (sig. = 0.000). Tamhane multiple comparisons test was applied. According to result, the use of metal wire in structure significantly increased the rigidity of the samples as noted in previous studies [40]. However, the metal type has no significant effect on the stiffness of knitted fabrics.

CONCLUSION

In the study, the metal wires were successfully intermingled with two PA yarns and knitted into 1×1 rib fabrics with a flat knitting machine. Technical (EMSE, surface resistivity and antibacterial activity) and physical (bending rigidity) properties of metal composite knitted fabrics were investigated. Results of study summarized below.

- All knitted fabrics had lower EMSE value than 10 dB for wale direction. Double layer samples provided significantly higher EMSE then single layer samples. In addition, the difference in the number of layer did not cause a significant change in the absorbed and reflected power ratio. Metal types were significantly determinant on the absorbed and reflected power ratios. The samples containing SS showed higher reflected power ratio than Cu and Ag samples respectively. It was observed that different metal types react differently by the change in the number of layers. The increase in the number of layers was significantly increased the performance of the silver composite sample and double layer Ag samples showed higher EMSE than SS and Cu samples respectively.
- There was a negative correlation at moderate level for both single and double layer samples. It can be said that the double layer samples provided more stable shielding than single layer against the shorter wavelength.
- Segmented data analysis showed that the metals had different performance in different frequency ranges. In the range of 1–3 GHz, stainless steel had a better EMSE than copper and silver, the

performance of copper came into prominence between 3 and 5 GHz for single layer samples. It was determined that the increase in the number of layers significantly increases the performance of samples containing silver. AgD samples showed the best performance especially in the 3–5 GHz range.

- Reflected power ratio of SS sample higher than CuS and AgS samples between 1 and 3 GHz frequency ranges. CuS samples came into prominence with reflected power ratio between 3 and 5 GHz similarly the EMSE results. AgS sample showed a better absorbed power ratio between 1 and 3 GHz and 4 and 5 GHz ranges. There was no significant difference among the metal types in terms of the absorbed and reflected power ratio values between 4 and 5 GHz ranges.
- The surface resistivity of the control fabric was higher than 10^{12} ohm/sq. In this case, the control sample classified as isolative. The use of Cu and SS wire extremely reduced the resistivity and structure became conductive with the value less than 10^3 ohm /sq.
- Antibacterial activity tests showed that the copper composite knitted fabrics provided 99 % antibacterial (bactericidal) activity against *K. pneumoniae* and *S. aureus* bacteria.
- The use of metal wire in structure significantly increased the rigidity of the samples more than twice.

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