Reflection EMI Shielding Effect On Graphen/Cuo Silicon Rubber Nanocomposites Over Broad Frequency Range Of 1 Ghz To 20 Ghz

Vishal Deore[1,2*], Sneha Singh[2], Harish Shinde[2], Vaibhav Shelar[3], Amol Ladhe[4], Harsh Gaikwad[5], Avinash Shinde[2], Milinda Mahajan[1], I. Siva[6], Smita Waghmare[7]

[1] *Department of Technology, Savitribai Phule Pune University, Pune - 411007, MH, India*
[2] *Cummins College of Engineering for Women, Pune - 411052, MH, India*
[3] *Trinity College of Engineering and Research, Pune 411048, MH, India*
[4] *Vishwakarma institute of technology, Bibwewadi, Pune - 411 037, MH, India*
[5] *Modern College of Arts, Science and Commerce Shivaji Nagar Pune 411005, (M.S) India*
[6] *Department of Mechanical Engineering, Mohan Babu University, Tirupati 517102, AP, India*
[7] *MES's Nowrosjee Wadia College, Pune - 411001, MH, India*

**Corresponding Authors:- Vishal Deore*
**Email:- vishal.deore@cumminscollege.in*

A material's conductivity, permittivity, and permeability all affect absorption and reflection losses, which are the primary determinants of EMI shielding. Using the features of nanofillers such as graphene and CuO, we have attempted to enhance the dielectric properties, focused shielding effectiveness, and EMI shielding of the silicon rubber polymer composite in the current work. In the automotive, aerospace, electronics, and many industrial industries, lightweight elastomer nanocomposites have numerous applications. Mechanical characteristics in items shouldn't be compromised in any way. CuO graphene silicone rubber, as a material for nanocomposite, is being developed with help from this study. The technique of blending and molding in order to prepare nanocomposites. A hot air oven was used for the final curing after the molding process, which was completed at 180 degrees Celsius. Filler with varying weight percentages of 0, 1, 2, 4, and 8% graphene and a constant 1% CuO are used for testing. Additionally, the samples' dielectric characteristics and electromagnetic wave shielding effectiveness (SE) values were examined at operating frequencies in the range of 1 GHz to 20 GHz. As frequency increases, shielding efficiency SE because to reflection increases. Maximum SE reflection of -33 dB for specimen nSR4 at 17 GHz. Additionally, nSR6 and nSR5 specimens work well in the 4 GHz to 10 GHz range.

Keywords: EMI SE, Silicon Rubber(SR), nanocomposites nSR, CuO, Graphene

1. Introduction

The manuscript explores [1] by P. Murugaiyan et al. the electromagnetic interference (EMI) shielding effectiveness (SE) of amorphous and nanocomposite soft magnetic ribbons. The paper is scientifically thorough, offering an in-depth analysis of the electromagnetic properties of these materials and their relevance in practical applications such as reducing electromagnetic pollution. The novelty lies in comparing amorphous and nanocomposite materials, which the authors have characterized through detailed experiments. Along with the paper [2] could further improve by exploring long-term stability under operational conditions, such as mechanical fatigue or environmental degradation, which would add to its practical applications. Additionally, it would be valuable to examine how these composites perform in large-scale production processes. Nevertheless, the manuscript presents a compelling case for the integration of HfC-carbon fiber composites in next-generation EMI shielding applications. Whereas H. Guan [3] compares the performance of carbon fibres with and without nickel coating to provide a thorough analysis of the impact of planar coil and linear layouts of continuous carbon fibre tow on EMI shielding efficacy. The work focusses on maximising EMI shielding through the arrangement and coating of fibres, offering a thorough knowledge of how structural changes might improve performance. With its emphasis on carbon fibre configurations and coating optimisation, this paper makes a significant addition to the subject of EMI shielding and has a great deal of promise for practical use. Clear data on the effects of foam density, MWCNT content, and microstructural features on shielding performance are provided in the methodologically sound work [4]. Nevertheless, more attention to the material's long-term resilience and thermal stability in actual settings should improve the research's usefulness. All things considered, the work makes a significant addition to the field of EMI shielding materials, especially for applications requiring materials that are lightweight and multipurpose. The novel part of [5] study is the production of a graphene/AgNWs composite, which overcomes a major obstacle in the area by striking a fine compromise between optical transparency and shielding efficacy. Superior electrical conductivity and EMI shielding capabilities are a result of the scientists' careful manufacturing technique, which ensures uniform dispersion and strong interfacial adhesion between graphene and AgNWs. All things considered, Myungjun Jung et al. and D. Micheli [6, 7] significantly advance the area of innovative building materials by showcasing the potential of CNT-reinforced UHPC as a multipurpose material that may solve structural and electromagnetic issues in contemporary building. Additionally, a clearer analysis of the economic feasibility of scaling this technology for large-scale construction projects could enhance the practical impact of this research. Overall, the paper contributes significantly to the development of multifunctional materials for modern building infrastructures.

The usefulness of cenosphere composite films coated with polyaniline-nickel oxide (PANI-NiO) for shielding electromagnetic interference is investigated by the researcher [8]. The work focusses on using the special qualities of cenospheres—lightweight, hollow particles—to produce EMI shielding materials that are both efficient and lightweight. High electrical conductivity and magnetic characteristics are added by including NiO, a metal oxide, and PANI, a conducting polymer. This research's unique material design, which strikes a compromise between high-performance shielding and lightweight design, is its main strength. The paper [9] offers a novel method for increasing the efficiency of electromagnetic interference shielding via spinnable multiwall carbon nanotubes (MWCNTs) patterned orthogonally. The work focusses on how MWCNT orientation and arrangement may greatly affect the material's EMI shieldng capabilities, making it applicable to applications in telecommunication, aerospace, and wearable electronics. Bluma G. Soares et al.'s [10] study is strong because it takes a thorough approach to comprehending the function of ionic liquids as dispersants and functional additives. The electrical conductivity, rheological behaviour, and EMI shielding efficacy of the composite are all thoroughly reported by the authors. This work is pertinent to coatings and electronics applications because it emphasises the role that dispersion plays in getting optimal performance in MWCNT-based composites. The authors [11] successfully demonstrate that the integration of MWCNT coatings improves the electrical conductivity and EMI shielding effectiveness of the fabrics. Additionally, the study provides comprehensive data on the mechanical performance of the coated fabrics, including tensile strength and durability under different conditions. The fabrication of ultra-lightweight 3D reduced graphene oxide (rGO) aerogels embellished with zinc oxide and cobalt ferrite nanoparticles for EMI shielding applications is explored in the work [12]. Combining rGO with dielectric and magnetic nanoparticles is a unique way to increase these aerogels' shielding efficacy without sacrificing their low density, which makes the material ideal for electrical and aeronautical applications. The effect of silica fume additives on the electromagnetic interference shielding efficacy of multi-walled carbon nanotube (MWCNT)/cement composites is examined by researchers I.W. Nam et al. [13]. Research on the incorporation of MWCNTs into cement composites is expanding, especially for building materials that need to provide both EMI shielding and structural integrity, as those used in the construction of military installations or sensitive buildings. The goal of the paper [14] is to improve the efficiency of EMI shielding in polycarbonate/graphene nanocomposites made using a one-step supercritical carbon dioxide foaming method. Although applying a supercritical foaming technique to improve electrical conductivity and EMI shielding is a well-established method, it brings something new to the material's growth. Graphene is a well-known substance. simultaneously the research article [15] compares (EMI) shielding effectiveness of carbon nanofiber (CNF) and nanofibrillated cellulose (NFC) composites.

The authors [16] systematically evaluate different fiber configurations and demonstrate that the lay-up pattern has a considerable impact on the EMI shielding properties. The study provides thorough experimental data, illustrating that certain configurations enhance the alignment of carbon fibers, thus improving conductivity and shielding effectiveness. The electrical contact between the specimen and the testing fixture is a crucial but sometimes disregarded component in the assessment of EMI shielding efficacy, as discussed in the work [17]. The study concentrates on carbon-based materials and emphasises how crucial it is to maintain correct electrical contact throughout testing in order to prevent inaccurate measurements of shielding efficacy. The study [18] highlights the unique properties of carbon-based materials, such as high electrical conductivity, light weight, and thermal stability, which make them suitable for EMI shielding applications in industries like telecommunications, aerospace, and military specifically focusing on their effectiveness in the X-band frequency range (8–12 GHz). The authors D.P. Schmitza et al. [19] assess the impact of carbon fillers, such as graphene and carbon nanotubes, on the electrical conductivity and shielding properties of the ABS matrix. The results indicate that the proper distribution of carbon materials within the polymer matrix can significantly enhance the EMI shielding performance, with higher concentrations of conductive fillers leading to increased effectiveness. By focusing on the alignment of MWCNTs, the paper [20] addresses a key challenge in the fabrication of carbon nanotube-based composites—achieving uniform dispersion and directional alignment for optimal performance. The authors D.W. Lee et al. report that aligned nanotubes create a more continuous conductive network, which is critical for maximizing shielding effectiveness, particularly at higher frequencies.

The authors, which include Revathy Ravindren [21], concentrate on developing materials that combine excellent shielding performance with flexibility by using conductive fillers like graphene and carbon nanotubes in flexible polymer blends. The study emphasises the significance of creating a twofold percolation network, in which conductive fillers are concentrated at the polymer blend interface to improve electrical conductivity and EMI shielding without materially sacrificing the material's flexibility. Even at very low filler concentrations, the experimental results demonstrate that this selective distribution of fillers may produce nanocomposites with outstanding shielding efficiency. The inclusion of copper nanowires into flexible polymer mix nanocomposites is explored in the study [22], which expands on the idea of double percolation. they create a model that can forecast the percolation threshold with enough accuracy to enable filler content to be optimised for maximal shielding while using the least amount of material. The research paper [23] explores the synergistic effect of hybrid fillers, specifically graphene and multiwalled carbon nanotubes (MWCNTs), on the mechanical, electrical, and shielding properties of polycarbonate (PC) and ethylene methyl acrylate (EMA) nanocomposites The findings highlight that the combination of these two conductive fillers results in a percolation network that promotes better charge transport, which is crucial for EMI shielding. The Research looks into [24] A silicone rubber matrix is mixed with synthetic nickel particles to create a conductive composite that can reduce electromagnetic radiation. Although the study effectively illustrates the potential of nickel/silicone composites for electromagnetic interference shielding, additional comparison information on other conductive filler types and matrix materials could have been included. Furthermore, additional research on these composites' ability to withstand harsh environments might increase their usefulness. All things considered, the work makes a major contribution to the creation of EMI shielding materials for industrial use. The dielectric behaviour and EMI shielding efficacy of styrene butadiene rubber (SBR) composites containing MWCNTs modified by ionic liquid are examined in the work [25]. The findings demonstrate that, in order to achieve high shielding efficiency, the modified MWCNTs must form a more continuous conductive network within the rubber matrix. The [26] study investigates how thermal-air ageing affects the EMI shielding efficacy and mechanical characteristics of nanostructured carbon-filled chlorinated polyethylene (CPE) composites. This shows that the carbon fillers' conductive network is resistant to thermal ageing, which qualifies these composites for extended usage in hot conditions. All things considered; our study shows that inexpensive nanostructured carbon-filled CPE composites can provide effective EMI shielding in industrial settings.

The review article of Qingsen Gao et al. [27] provides a comprehensive overview of the use of polymer/MXene composites for electromagnetic interference (EMI) shielding applications. MXenes, two-dimensional materials with outstanding electrical conductivity and mechanical strength, are highlighted as highly promising fillers in polymer matrices. also discusses the role of MXenes in enhancing electrical conductivity and absorption-based EMI shielding, which is more efficient than traditional reflection-based methods. The research [28] highlights the advantages of using core-shell particles, which consist of a magnetic core coated with a protective shell. This design not only enhances EMI absorption particularly in the GHz frequency range but also improves the compatibility between the reinforcement and the magnesium matrix, leading to superior mechanical properties. The possibility of biocomposites as greener substitutes for EMI shielding applications is investigated by the writers Vinoth Kumar et al. [29]. With an emphasis on their mechanical, electrical, and electromagnetic interference shielding qualities, the study contrasts many biocomposites, including natural fiber-reinforced polymers. These materials' potential to support environmental sustainability is highlighted by the utilisation of renewable resources in their development. According to the results [30], the nickel-filled composites have notable mechanical flexibility and robustness in addition to good EMI shielding performance across a broad frequency range. The investigation also looks at how the size and distribution of nickel particles affect overall shielding efficacy, coming to the conclusion that uniform dispersion is essential to getting the best outcomes.

The review [31] presents a thorough analysis of various polymers and filler materials used to improve the performance of these composites. It methodically explores various synthesis approaches, the role of filler materials (e.g., carbon nanotubes, graphene, and metal nanoparticles), and how these affect the electrical conductivity and shielding effectiveness. In addition to discussing the promise of conducting polymers as flexible, lightweight, and efficient EMI shielding materials, the study highlights the special qualities of polyaniline (PANI), polypyrrole (PPy), and polythiophene. The notion of microbial-induced calcite precipitation (MICP) is presented in the study [32] as a sustainable way to improve the strength and longevity of concrete while lowering its carbon footprint. The authors give a thorough explanation of how microorganisms may strengthen concrete, extend the life of structures, and naturally fix cracks in it. The evaluation also covers the use of EMI methods, which provide an effective and non-destructive way to assess structural health, to monitor the state of concrete structures. This creative method shows how biological systems and cutting-edge monitoring technology may be integrated in the building sector. The paper by Bijulin Greety DJ [33] addresses several EMI shielding strategies, such as the newly popular application of nanocomposites and more conventional metal-based approaches. The promise of electrospun nanocomposites—which are composed of a polymer matrix and conductive fillers like graphene or carbon nanotubes (CNTs)—to provide enhanced shielding qualities without sacrificing the flexibility and low weight that are essential for materials used in aircraft construction is emphasised.

2. Experimental Section

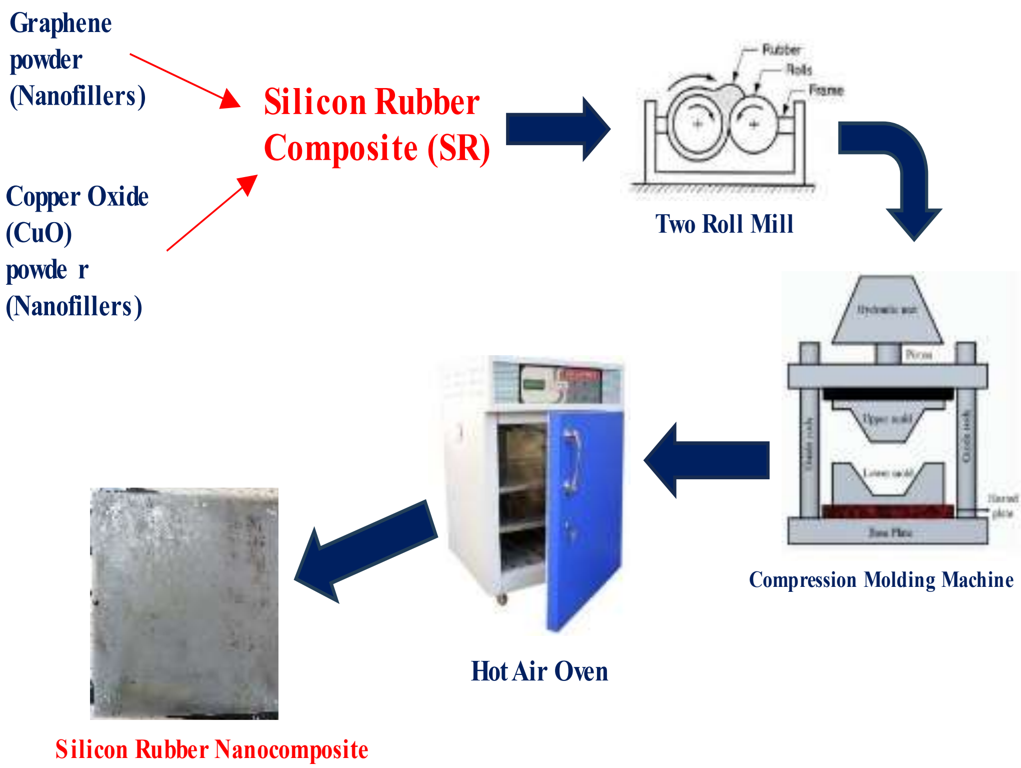

Fig 1. Scheme of Graphene, CuO Silicon Rubber nanocomposites preparation via Melt blending Method

2.1 Materials

Using Graphene, Copper Oxide (CuO) nanofillers in the nanopowder forms mix with Silicon Rubber composites were prepared by in melt blending method shown in schematic dig. 1. Such silicon rubber composition adding nanofillers for nSR and its composites were made. These terms will be used to refer to the items throughout the paper for the sake of ease of understanding. Di-cup 40 (DCP), a curing agent, and silicon rubber (SR) of grade SH5060U are supplied by Pune, India-based Krupa Chemicals. Silicon Rubber (SR) properties of Specific Gravity 1.16 g/cc, ultimate tensile strength 5.5 MPa and hardness 50 (A). A purity level of >99% for graphene-D was provided by Adnano, Banglore, India. The graphene sheet has a length of 10 nm, a diameter of less than 20 µm, and five to ten layers. The graphene sheet is typically 5–10 nm thick. Graphene properties of Specific Gravity 1.6 g/cc, ultimate tensile strength 132 GPa and hardness 70 HRC. In addition, they simultaneously supplied Copper Oxide Nanoparticles (CuO) with a purity level of >99% and a particle size of about < 100 nm. Copper oxide (CuO) properties of Specific Gravity 5.5 g/cc, ultimate tensile strength 200 MPa and hardness 4 Mohs scale.

2.2 Preparation of Polymer Nanocomposites

The graphene-based Silicon Rubber (SR) compounds nSR1 of pure silicon rubber, nSR2, nSR3, nSR4, nSR5, and nSR6 specimens have different graphene weight fractions of 0, 1, 2, 4, and 8%, respectively. Additionally, each specimen receives a constant 1% of CuO and 2% of DCP (Dicup 40) as a curing agent compound. The names assigned to these graphene weight fractions for the nanocomposite specimens are nSR1, nSR2, nSR3, nSR4, nSR5, and nSR6. The manufacturing method is eventually shown in Figure 1, which also shows the material composition of Silicon Rubber SR nanocomposite. In a machine with two rollers, the first step of the process combines silicon rubber (SR) with graphene and copper oxide (CuO) as a nanofiller. The compound is then moulded of size 150 x 150 x 3 mm using a compression moulding machine set at 180°C for 300 seconds at a moulding pressure of 50 bars. The post-curing process is carried out in a hot air oven at 200°C for four hours.

2.3 Experimental particulars

Six samples of each unique composition are used to test a number of dielectric and EMI SE reflections. Additionally, FESEM studies are carried out to verify graphene dispersion and comprehend the composite's development. The details of each previously discussed characterization will be covered in the parts that follow. Additionally, an XRD device (Rigaku Miniflex 600 XRD) was used to analyze the SR and hybrid composites. Using Cu K radiations (=0.154 nm) in X-rays and a dispersion theta ranging from 20o to 80^0.

2.4 Dielectric and Shielding Effectiveness Reflection Analysis

The Agilent PNA N522A Vector Network Analyzer's S parameters (S11) were used to calculate shielding efficiency. The coaxial cables, waveguide adaptors, and sample holders utilised in this experiment were compatible with frequencies between 1 GHz and 20 GHz. The waveguide's and the sample holder's inner cross sections measure 0.9 in by 0.4 in. The inner diameter of the coaxial cable is 7 mm. The observed scattering characteristics were used to compute the complex dielectric permittivity (ε). In particular, the Nicolson-Ross-Weir technique was applied. As advised by Agilent materials measurements, all samples had a thickness of 3 mm for the S parameter measurements. According to the Vector Network Analyser (VNA Agilent Technologies) instruction manual, a rectangular waveguide is advised for the 1 GHz to 20 GHz frequency spectrum. A coaxial measuring line is better ideal for these kinds of frequency testing. For silicon rubber (nSR) nanocomposites, Fig. 2 [34] displays the observed frequency-dependent complex permittivity real part (ε′), complex permittivity imaginary part (ε″), and dielectric loss tangent (tan δ). Decibels (dB) are used to express the shielding efficiency values.

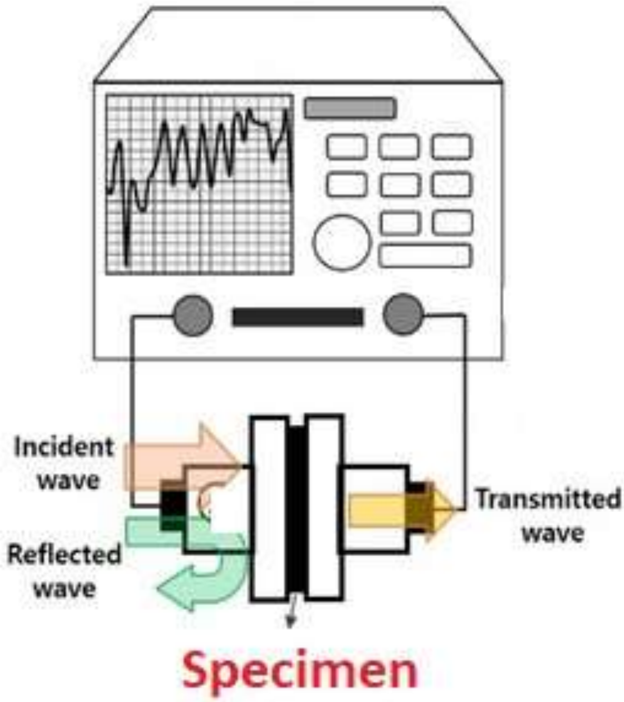

Fig.2 Vector Network Analyzer (VNA) Schematic Diagram (reference [34])

3. Results and Discussion

3.1 XRD

One effective analytical method for determining a material's crystalline structure is X-ray diffraction, or XRD. The intensity of X-rays scattered by the crystalline material as a function of the angle of diffraction—typically designated 2θ, the angle between the incoming X-ray and the detected scattered X-ray—is shown by the XRD graph, also called a diffractogram. In order to validate the phase of nSR, X-ray diffraction (XRD) was performed on graphene and CuO nanoparticles, as shown in Figure 3. nSR1, nSR2, nSR3, nSR4, nSR5, and nSR6 are allocated to nanocomposites centred at 2θ = 28.7, 28.5, 26.51, 26.84, 26.468, and 26.559, respectively. The powder's nanocrystalline size is shown by the widening of the peaks. But when the data is evaluated using the nSR4, nSR5, and nSR6 compositions, the peak's strength is reduced, as seen by the peaks that appear at 26.84, 26.468, and 26.559, respectively. This indicates that graphene particles exist independently in the nSR4, nSR5, and nSR6 compositions. The production of a polymer composite that is reinforced with graphene is the outcome of the imposition of nSR polymer molecules, which has no effect whatsoever on the crystalline structure of graphene.

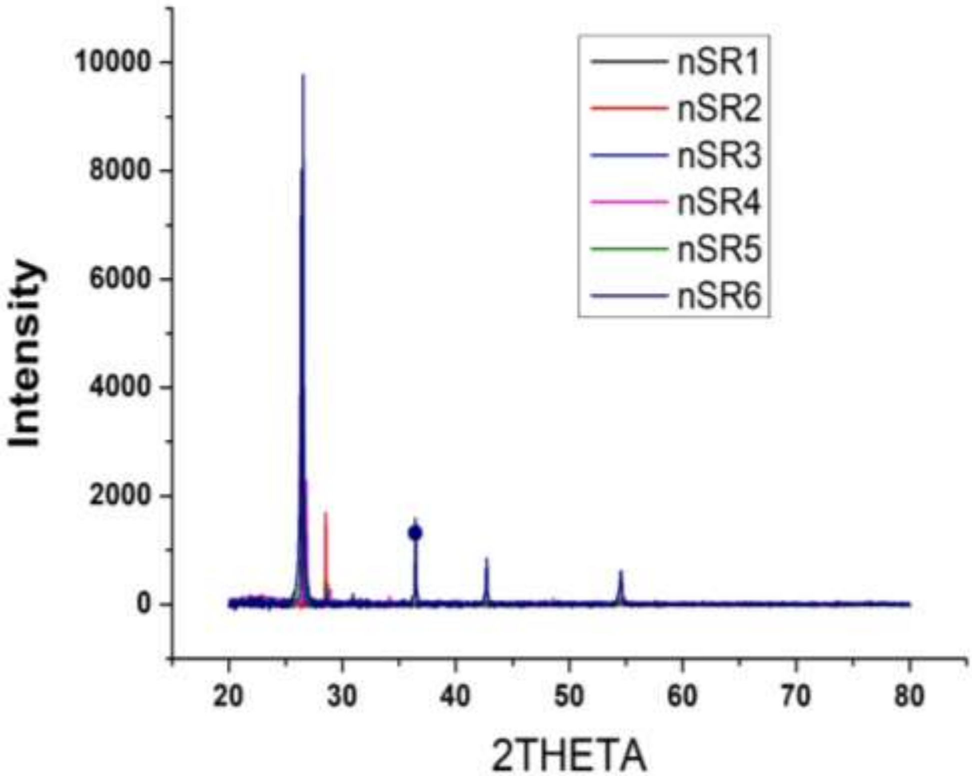

Fig. 3 X-ray diffraction patterns of all 6 Specimen for SR nanocomposites

3.2 Dielectric Parameters

A shielding material's ability to reduce electromagnetic radiation is mostly based on one of its EM properties, such as complex permittivity. It is crucial that these characteristics are estimated. Complex dielectric permittivity is composed of both imaginary and real components. Permittivity theory states that an electric field exerted on a material will cause two different kinds of electrical currents to flow through it: displacement current and

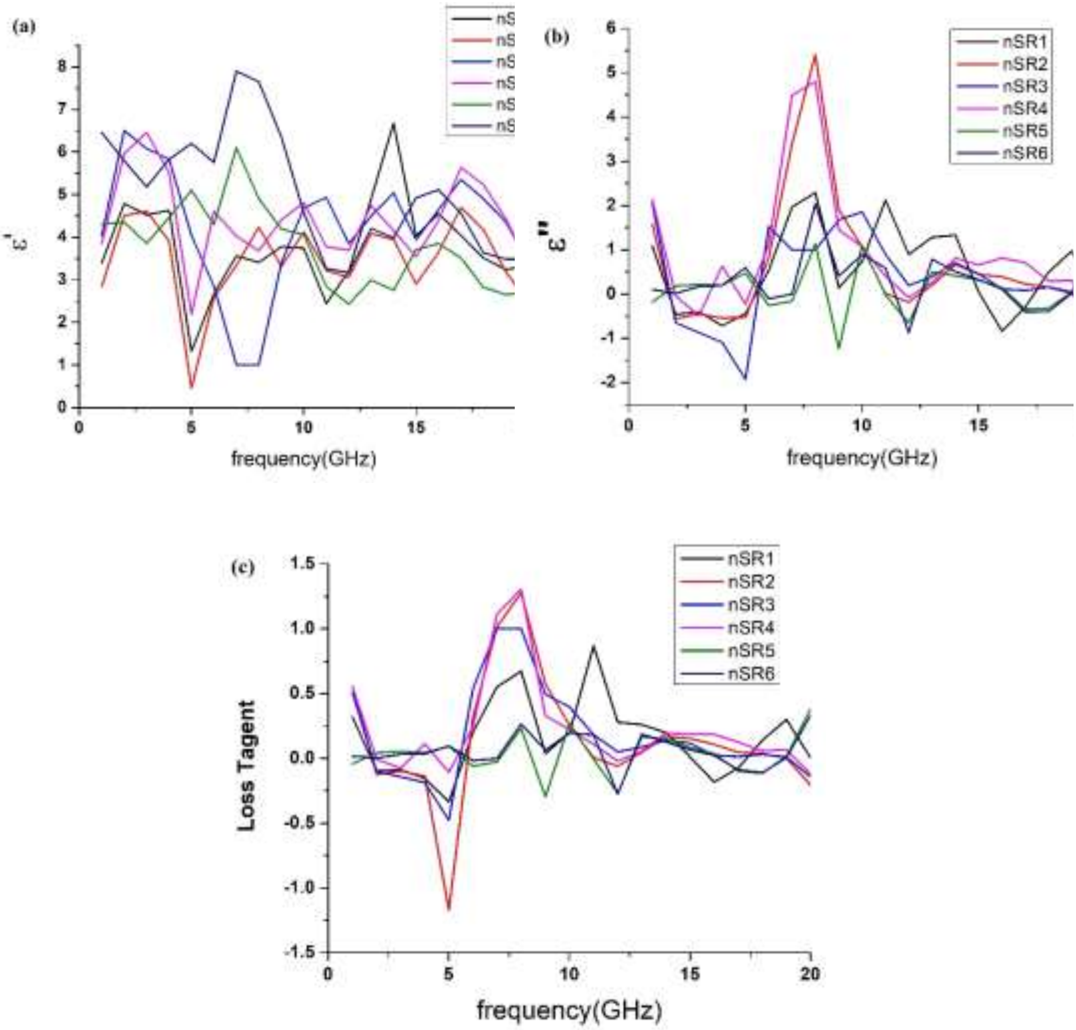

Fig. 4 (a) complex permittivity real part (ε′); (b) complex permittivity imaginary part (ε″); (c) dielectric loss tangent (tan δ) vs frequency 1 GHz to 20 GHz

conduction current. The former results in an imaginary fraction of permittivity (e’’) and emerges because free electrons are present for conduction. The latter results in a real portion of permittivity (e’) and is caused by bound charges, or polarisation. From the given result shown in figure 4 shows that real and imaginary part of permittivity performance for all 6 specimens during broad frequency band of 1 GHz to 20 GHz. So, result of both complex permittivity real part (ε′) and complex permittivity imaginary part (ε″) has been observed that nSR6, nSR5 better perform comparing to all other nSR4, nSR3, nSR2 and pure silicon rubber (nSR1) nanocomposite in between 4 GHz to 10 GHz frequency band. simultaneously, in case of dielectric loss tangent (tan δ) nSR5 has little better improvement shows compare with nSR6 and whereas nSR5, nSR6 comparatively more effective than other specimen of nSR4, nSR3, nSR2 in the frequency range of 5.2 GHz to 10.2 GHz.

3.3 EMI Shielding Reflection Effective (SE_R)

The effectiveness of materials' electromagnetic shielding may be determined using a vector network analyser. It gauges the different signals' phases and intensities. It is possible to compute the reflection losses using the S parameters S11 or the scattering parameters. The calculation of shielding effectiveness of reflection is as follows:

$R = (S_{11})^2 = (S_{22})^2$

Where R is reflectance.

Hence, The Reflection loss SE_R can be given as

$SE_R = -10 \log(1 - R)$

The SE values for each specimen sample's reflection loss of nSR are displayed in Figure 5. Across the whole operating frequency range, the SE values for the reflection loss rise as the frequency of the given nSR specimen samples increases. Particularly for the specimen of nSR5, it has been noted that nSR6 SE values significantly increase in the frequency range of 1 GHz to 8 GHz. Additionally, these two specimens perform better when compared to the other four nSR4, nSR3, nSR2, and pure SR samples. While nSR5 and nSR6 perform poorly between 8 and 12 GHz as compared to other specimens, nothing particularly changes between 12 and 20 GHz. However, it has also been shown that nSR4 performs noticeably better than other samples between 16 and 18 GHz. The theory of EMI shielding states that a decrease of at least or close to 20 dB over the frequency range of interest is a common objective for EMI shielding efficacy.

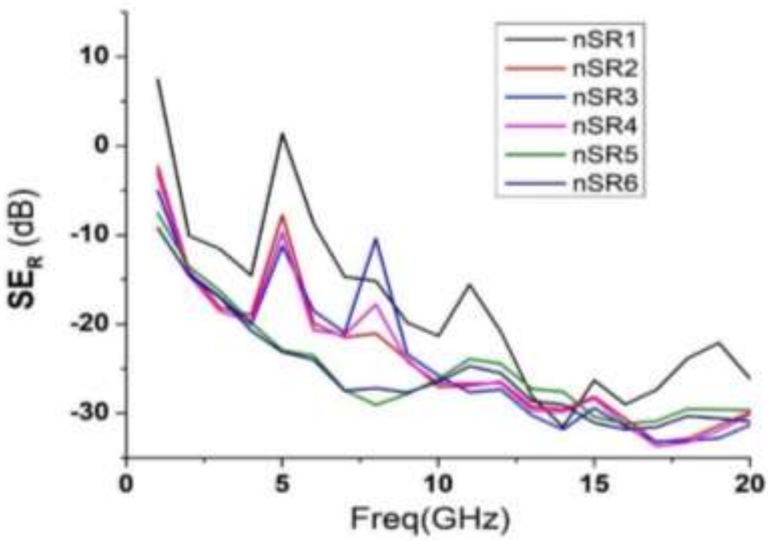

Fig. 5 EMI shielding Reflection component (SE_R) in the range of 1 GHz to 20 GHz

4. Conclusion

In this work, a two-roll mill and compression moulding were used to create the graphene CuO Silicon Rubber nanocomposites. However, the significant peak in the XRD interpretation does lead to the creation of a polymer composite reinforced with CuO and graphene. Results of real and imaginary complex permittivity, dielectric loss tangent is vary from various ranges frequencies. The EMI-SE of the nanocomposites, evaluated in the 1 GHz–20 GHz frequency range, increased gradually as the nanoparticle content increased. However, for the 4 vol.% Graphene and 1% CuO nanocomposite in the nSR4 specimen, it climbed abruptly to a value of 32.5 dB at 18 GHz. Reflection EMI SE of sample nSR6, nSR5 got upto 20% increases than others. The frequency range of 1 GHz to 8 GHz is greatly increased by SE reflection values, however nSR5 and nSR6 perform badly in comparison between 8 and 12 GHz. Not many of the anticipated changes were seen afterwards.

References

1) P. Murugaiyan, A. Mitra, A.K. Panda, A.S. Kumar, R.K. Roy, K. Manna, S.K. Srivastava, Electromagnetic interference shielding effectiveness of amorphous and nanocomposite soft magnetic ribbons, Physica B: Physics of Condensed Matter (2019), doi: https://doi.org/10.1016/j.physb.2019.05.017.
2) S. Tian, L. Zhou, Z. Liang, Y. Wang, Y. Yang, X. Qiang, Z. Qian, Electromagnetic interference shielding effectiveness of a flexible carbon fiber felt containing in situ grown hafnium carbide nanowires and nanobelts, Ceramics International (2019), doi: https://doi.org/10.1016/j.ceramint.2019.06.039.
3) H. Guan, D.D.L. Chung, Effect of the planar coil and linear arrangements of continuous carbon fiber tow on the electromagnetic interference shielding effectiveness, with comparison of carbon fibers with and without nickel coating, Carbon (2019), doi: https://doi.org/10.1016/j.carbon.2019.06.085.
4) Xun Fan, Guangcheng Zhang, Jiantong Li, Zhengyang Shang, Hongming Zhang, Qiang Gao, Jianbin Qin, Xuetao Shi. Study on foamability and electromagnetic interference shielding effectiveness of supercritical CO2 foaming epoxy/rubber/MWCNTs composite. Composites Part A: Applied Science and Manufacturing Volume 121, June 2019, Pages 64-73. https://doi.org/10.1016/j.compositesa.2019.03.008
5) Ning Zhang, Zhe Wang, Rongguo Song, Qianlong Wang, Hongye Chen, Bin Zhang, Haifei Lv, Zhi Wu, Daping He. Flexible and transparent graphene/silver-nanowires composite film for high electromagnetic interference shielding effectiveness. Science Bulletin 64 (2019) 540–546. https://doi.org/10.1016/j.scib.2019.03.028
6) Myungjun Jung, Young-soon Lee, Sung-Gul Hong, Juhyuk Moon. Carbon nanotubes (CNTs) in ultra-high performance concrete (UHPC): Dispersion, mechanical properties, and electromagnetic interference (EMI) shielding effectiveness (SE). Cement and Concrete Research Volume 131, May 2020, 106017. https://doi.org/10.1016/j.cemconres.2020.106017
7) D. Micheli, A. Vricella, R. Pastore, A. Delfini, R. Bueno Morles, M. Marchetti, F. Santoni,L. Bastianelli, F. Moglie, V. Mariani Primiani, V. Corinaldesi, A. Mazzoli, J. Donnini. Electromagnetic properties of carbon nanotube reinforced concrete composites for frequency selective shielding structures. Construction and Building Materials 131 (2017) 267–277. http://dx.doi.org/10.1016/j.conbuildmat.2016.11.078
8) Pritom J. Bora, K.J. Vinoy, Praveen C. Ramamurthy, Kishore, Giridhar Madras. Electromagnetic interference shielding effectiveness of polyaniline-nickel oxide coated cenosphere composite film. Composites Communications Volume 4, June 2017, Pages 37-42. http://dx.doi.org/10.1016/j.coco.2017.04.002
9) D.W. Lee, H. Kim, J.H. Moon, J.-H. Jeong, H.J. Sim, B.J. Kim, J.S. Hyeon, R.H. Baughman, S.J. Kim, Orthogonal pattern of spinnable multiwall carbon nanotubes for electromagnetic interference shielding effectiveness, Carbon (2019), doi: https://doi.org/10.1016/j.carbon.2019.05.052.
10) Bluma G. Soares, Nathan Riany, Adriana A. Silva, Guilherme M.O. Barra, Sebastien Livi. Dual-role of phosphonium – Based ionic liquid in epoxy/MWCNT systems: Electric, rheological

behavior and electromagnetic interference shielding effectiveness. European Polymer Journal 84 (2016) 77–88. http://dx.doi.org/10.1016/j.eurpolymj.2016.09.016

11) Zheng-Ian Lin, Ching-Wen Lou, Yi-Jun Pan, Chien-Teng Hsieh, Chen-Hung Huang, Chien-Lin Huang, Yueh-Sheng Chen, Jia-Horng Lin. Conductive fabrics made of polypropylene/multi-walled carbon nanotube coated polyester yarns: Mechanical properties and electromagnetic interference shielding effectiveness. Composites Science and Technology 141 (2017) 74-82. http://dx.doi.org/10.1016/j.compscitech.2017.01.013
12) Shivam Gupta, Sanjeev Kumar Sharma, Debabrata Pradhan, Nyan-Hwa Tai. Ultra-light 3D reduced graphene oxide aerogels decorated with cobalt ferrite and zinc oxide perform excellent electromagnetic interference shielding effectiveness. Composites Part A: Applied Science and Manufacturing Volume 123, August 2019, Pages 232-241. https://doi.org/10.1016/j.compositesa.2019.05.025
13) I.W. Nam, H.K. Kim, H.K. Lee. Influence of silica fume additions on electromagnetic interference shielding effectiveness of multi-walled carbon nanotube/cement composites. Construction and Building Materials 30 (2012) 480–487. http://dx.doi.org/10.1016/j.conbuildmat.2011.11.025
14) G. Gedler, M. Antunes, J.I. Velasco, R. Ozisik. Enhanced electromagnetic interference shielding effectiveness of polycarbonate/graphene nanocomposites foamed via 1-step supercritical carbon dioxide process. Materials and Design 90 (2016) 906–914. http://dx.doi.org/10.1016/j.matdes.2015.11.021
15) V. P. Anju, M. Manoj, Pezholil Mohanan, Sunil K. Narayanankutty. A comparative study on electromagnetic interference shielding effectiveness of carbon nanofiber and nanofibrillated cellulose composites. Synthetic Metals Volume 247, January 2019, Pages 285-297. https://doi.org/10.1016/j.synthmet.2018.12.021
16) D.D.L. Chung, A.A. Eddib, Effect of fiber lay-up configuration on the electromagnetic interference shielding effectiveness of continuous carbon fiber polymer-matrix composite, Carbon (2018), doi: https://doi.org/10.1016/j.carbon.2018.09.081.
17) A.A. Eddib, D.D.L. Chung, The importance of the electrical contact between specimen and testing fixture in evaluating the electromagnetic interference shielding effectiveness of carbon materials, Carbon (2017). http://dx.doi.org/10.1016/j.carbon.2017.02.091
18) Shivam Gupta, Nyan-Hwa Tai, Carbon Materials and Their Composites for Electromagnetic Interference Shielding Effectiveness in X-band, Carbon (2019). Doi:10.1016/j.carbon.2019.06.002
19) D.P. Schmitza, L.G. Eccoa, S. Dulb, E.C.L. Pereir , B.G. Soares , G.M.O. Barra, A. Pegoretti. Electromagnetic interference shielding effectiveness of ABS carbon-based composites manufactured via fused deposition modelling. Materials Today Communications Volume 15, June 2018, Pages 70-80. https://doi.org/10.1016/j.mtcomm.2018.02.034
20) D.W. Lee, J. Park, B.J. Kim, H. Kim, C. Choi, R.H. Baughman, S.J. Kim, Enhancement of electromagnetic interference shielding effectiveness with alignment of spinnable multiwalled carbon nanotubes, Carbon (2018), doi: https://doi.org/10.1016/j.carbon.2018.10.076.
21) Revathy Ravindren, Subhadip Mondal, Krishnendu Nath, Narayan Ch. Das. Investigation of electrical conductivity and electromagnetic interference shielding effectiveness of preferentially distributed conductive filler in highly flexible polymer blends nanocomposites. Composites Part A: Applied Science and Manufacturing Volume 118, March 2019, Pages 75-89. https://doi.org/10.1016/j.compositesa.2018.12.012
22) Revathy Ravindren, Subhadip Mondal, Krishnendu Nath, Narayan Ch Das. Prediction of electrical conductivity, double percolation limit and electromagnetic interference shielding effectiveness of copper nanowire filled flexible polymer blend nanocomposites. Composites Part B: Engineering Volume 164, 1 May 2019, Pages 559-569. https://doi.org/10.1016/j.compositesb.2019.01.066
23) Nisha Bagotia, Veena Choudhary, D.K. Sharma. Synergistic effect of graphene/multiwalled carbon nanotube hybrid fillers on mechanical, electrical and EMI shielding properties of

polycarbonate/ethylene methyl acrylate nanocomposites. Composites Part B: Engineering Volume 159, 15 February 2019, Pages 378-388. https://doi.org/10.1016/j.compositesb.2018.10.009

24) Atefeh Heidarian, Hamed Naderi-Samani, Reza Shoja Razavi, Mahsa Nejad Jabbari, Ehsan Naderi-Samani. Synthesis of nickel particles for use in nickel/silicone rubber composites for the application of electromagnetic interference shielding gaskets. Heliyon 10 (2024) e24690. https://doi.org/10.1016/j.heliyon.2024.e24690
25) Abraham J, Arif P M, Xavier P, Bose S, George SC, Kalarikkal N, Thomas S. Investigation into dielectric behaviour and electromagnetic interference shielding effectiveness of conducting styrene butadiene rubber composites containing ionic liquid modified MWCNT, Polymer (2017), doi: 10.1016/j.polymer.2017.01.078.
26) Subhadip Mondal , Sayan Ganguly, Poushali Das, Poushali Bhawal, Tushar Kanti Das, Revathy Ravindren, Sabyasachi Ghosh, Narayan Ch. Das. Effect of thermal-air ageing treatment on mechanical properties and electromagnetic interference shielding effectiveness of low-cost nanostructured carbon filled chlorinated polyethylene. Materials Science and Engineering: B Volume 225, November 2017, Pages 140-149. http://dx.doi.org/10.1016/j.mseb.2017.08.024
27) Qingsen Gaoa, Xin Wanga, Dirk W. Schubert, Xianhu Liu. Review on polymer/MXene composites for electromagnetic interference shielding applications. Advanced Nanocomposites 1 (2024) 52–76. https://doi.org/10.1016/j.adna.2023.11.002
28) Z.Y. Xu, C.F. Fang, C.J. Li, S.Y. Shi, R. Wang, X.P. Zhang, J.T. Feng, Y.M. Wang. Core-shell magnetic particles reinforced magnesium matrix composites with an excellent combination of mechanical and electromagnetic interference shielding properties. Journal of Materials Research and Technology 27 (2023) 6593–6605. https://doi.org/10.1016/j.jmrt.2023.11.133
29) Vinoth Kumar Selvaraj, Jeyanthi Subramanian, Elammaran Jayamani, Shreya Viswanath, Karan Pandurengan, S. Siddharth, Prince Jeya Lal. A comparative study on biocomposites for electromagnetic interference shielding applications: A green initiative for environmental sustainability. journal of materials research and technology 2023 26 (5786-5800). https://doi.org/10.1016/j.jmrt.2023.08.290
30) Atefeh Heidarian, Hamed Naderi-Samani, Reza Shoja Razavi, Mahsa Nejad Jabbari, Ehsan Naderi-Samani. Synthesis of nickel particles for use in nickel/silicone rubber composites for the application of electromagnetic interference shielding gaskets. Heliyon 10 (2024) e24690. https://doi.org/10.1016/j.heliyon.2024.e24690
31) Maruthi N, Muhammad Faisal, Narasimha Raghavendra. Conducting polymer based composites as efficient EMI shielding materials: A comprehensive review and future prospects. Synthetic Metals 272 (2021) 116664. https://doi.org/10.1016/j.synthmet.2020.116664
32) Krishna Kumar Maurya, Tripti Sonker, Anupam Rawat. Sustainable concrete construction by microorganism and monitoring using EMI technique: A review. Materials Today: Proceedings https://doi.org/10.1016/j.matpr.2020.03.169
33) Bijulin Greety DJ, G. Jims John Wessley. A study on EMI shielding in aircraft: introduction, methods, and significance of using electrospun nanocomposites. Journal of Space Safety Engineering 11 (2024) 150–160. https://doi.org/10.1016/j.jsse.2024.01.001
34) Hyun-Ji Kim, Gi-Hwan Kang, Sung-Hoon Kim and Sangmoon Park. Enhancement in Electromagnetic Wave Shielding Effectiveness through the Formation of Carbon Nanofiber Hybrids on Carbon-Based Nonwoven Fabrics. Nanomaterials (MDPI) 2021, 11, 2910. https://doi.org/10.3390/nano11112910