Panamerican Mathematical Journal
ISSN: 1064-9735
Vol 35 No. 4s (2025)

Enhancing Sustainable Building Technology: A Study on Mechanical and Thermal Properties of Silicone Rubber and MWCNT Composites for Energy-Efficient Urban Infrastructure

J. Jayakanth [1,2], K. Chennakesavulu[1,2*], G. Ramanjaneya Reddy[2], Pallavi Sharma[3], Sakinah Mohd Shukri[4], Dasarathy A K[5], Rapeti Srinivasa Rao[6], Richa Sharma[7], Abhinav Kumar[8,9]**

[1]Department of Chemistry, Sathyabama Institute of Science and Technology

(Deemed to be University),Chennai - 600 119, India.

[2]Centre for Nano Science and Nano Technology, International Research Centre, Sathyabama Institute of Science and Technology (Deemed to be University), Chennai-600 119, India

[3]Department of Applied Science & Humanities, Model Institute of Engineering and Technology, Kot Bhalwal, Jammu, Jammu & Kashmir

[4]Management and Science University, Shah Alam, Selangor, Malaysia

[5] Department of Civil Engineering, School of Engineering and Technology, JAIN (Deemed to be University), Bangalore, Karnataka, India

[6]Department of Civil Engineering, Raghu Engineering College, Visakhapatnam, Andhra Pradesh-531162, India

[7]Computer Science Engineering, Lovely Professional University, Phagwara, India.

[8]Department of Mechanical Engineering and Renewable Energy, Technical Engineering College, The Islamic University, Najaf, Iraq

[9]Centre for Research Impact & Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, 140401, Punjab, India

Corresponding Author: chennanml@yahoo.com*, drabhinav3210@gmail.com**

Article History:

Received: *12-01-2025*

Revised: *05-03-2025*

Accepted: *13-03-2025*

Abstract:

This study explores the mechanical and thermal properties of silicone rubber composites reinforced with multi-walled carbon nanotubes (MWCNTs). By enhancing durability and thermal conductivity, these composites offer potential improvements in sustainable building practices, aligning with the goals of reducing material consumption and enhancing energy efficiency. Through systematic experimentation and analysis, the study investigates how the incorporation of MWNCT affects the mechanical strength and thermal conductivity of the silicone rubber matrix. Various properties such as tensile strength, modulus of elasticity, elongation at break, and thermal conductivity are evaluated to understand the composite's performance. The findings provide valuable insights into the potential applications of SR/MWNCT composites in industries requiring materials with enhanced mechanical and thermal properties, such as aerospace, automotive, and electronics. Our findings contribute to the development of sustainable building materials that support environmental performance and durability.

Keywords: *MWCNT; Silicone Rubber; Mechanical Properties; Thermal Properties*

1. Introduction

Silicone rubber is a versatile material crucial for diverse applications due to its durability, flexibility, resistance to extreme temperatures, and chemical inertness. It serves industries ranging from electronics to healthcare, including uses as flame retardants, strain sensor materials, EMI shielding materials, sensors, electrodes, sealants, water repellents, electrical gaskets, prostheses of human external organs, biomedical devices, thermal insulators for rocket motors, pressure-sensing skin in robotics, and thermoelectric materials [1–10]. However, improving the physicochemical properties of silicone rubber poses a challenge, particularly in the selection of filler materials and achieving homogeneous mixing within the silicone rubber matrix. Typically, inorganic fillers such as ZnO, TiO2, SiO2, Al2O3, and organic fillers like multiwall carbon nanotubes (MWCNTs), graphene, graphite, and carbon fibers are employed. Silicone rubber MWCNT composites offer enhanced mechanical strength, electrical conductivity, and thermal stability, which are essential for advanced applications. These properties can also contribute to sustainable building technologies by enhancing the durability and energy efficiency of building materials. For instance, improved thermal conductivity can optimize insulation in buildings, reducing energy consumption and aligning with sustainable development goals [11,12]. This study explores the mechanical and thermal properties of silicone rubber and MWCNT composites, highlighting their potential as innovative materials for sustainable construction and urban development.

The surface modified or 3-isocyanato propyltriethoxy silane functionalized carbon fibre with silicone rubber and degree curing has considerable effect on mechanical properties like tensile strength and thermal properties of silicone rubber composite [13]. The liquid silicone rubber with triethoxyvinylsilane functionalised graphene oxide thermal conductivity increases 2 fold, tensile strength increased to 2.3 fold, tear strength increased to 2.79 and shear strength increased up to 1.97 fold when compared to neat liquid silicone rubber [14]. The 0.5 wt% MWCNT/Al2O3/Silicone rubber thermal stability increases and MWCNT dissipate the heat in silicone rubber matrix [15]. The addition of 8% graphene nano plates in silicone rubber increase the thermal conductivity from 0.16 to 0.26 W/(m.K) and tensile strength increases from 0.240 to 0.648 MPa [16]. In Carbon Nanotubes /Polydimethylsiloxane composite, if the CNT wt% varies from 0.1 % to 5% at 2% the electrical conductivity of composite was saturated, but thermal conductivity increases [8]. The 0.5 % of MWCNT as secondary filler in Carbon fibre- Room temperature vulcanized Silicone rubber increases it's tensile and tear strength from 4.0 MPa, 20.3 kN.m-1 to 4.3 MPa, 21.3 kN.m-1 respectively [17]. The 2% of MWCNT was reinforced in Silicone rubber by ultra sonication and twin screw extruder and the evaluated tensile strength of the twin screw extruder method was higher when compared to ultra sonication, it was due to the fragmented tubes and higher dispersion in silicone matrix [18]. The light weight silicone rubber/MWCNT/Fe3O4 composite has superparamagenetic, thermal and EMI sheilding properties [19]. The mechanical properties like elastic modulus at 0.47 Poisson's ratio, ultimate strength were 2.94 MPa and 6.54 MPa respectively [4]. The liquid silicone rubber filled with 3% of carbon black enhances the tensile strength from 14.22 to 16.33 MPa and Compressive modulus from 40.86 to 54.21 MPa respectively [20]. The addition of carbon fibre to RTV silicone rubber increases the thermal stability and influence the tensile properties due to the poor interfacial interaction between RTV silicone rubber and carbon fibre [21]. The addition of nano silica particles in to RTV silicone rubber enhances mechanical properties like the tensile strength and elongation at break from 1,1 MPa to 3.05 MPa and 140% to 332% respectively [22]. In the present study the effect of filler i.e. MWCNT with various wt% on mechanical properties and thermal properties were studied and the optimized materials were further characterized for EMI sheilding test.

2. Material and Methods

The AR grade Zeolite, Nickel perchlorate were purchased from Merck. Silicone Rubber (SR), Dicumyl peroxide from Lakshmi Rubber Pvt. Ltd., Chennai.

2.1 Synthesis of MWCNT

The CNTs synthesized by methane decomposition on Ni-encapsulated zeolite in CVD reactor under atmospheric pressure. Quartz boat with Ni encapsulated zeolite (approx. 200 mg) placed in tubular furnace. Gradual heating to 950°C under argon (500 sccm) for 15 min. Argon-methane mix (200:10 sccm) fed for 1 h. The reactor was cooled under argon (500 sccm) and washed with 10% HF and MWCNTs were collected [3,23,24].

2.2 Characterization of MWCNT

Zeiss SUPRA 55, a FESEM with Schottky thermal field emission, offers 2nm imaging resolution, multiple detectors, and electron beam lithography capability was used for FESEM acquisition. The samples were prepared by dispersing the MWCNTs in ethanol and sputtered for 10 seconds. The JEOL 2100F - TEM is equipped with a Cs-corrected condenser, imaging filter, EDX, biprism, and two CCD cameras was used for MWCNT image acquisition.

The Surface area measurements were conducted using the BET ASAP 2020 Micrometrics system. Samples underwent 24-hour vacuum treatment at 50°C, followed by degassing at 70°C. Free space measurements utilized helium gas. FTRAMAN spectra were obtained via a RENISHAW Raman Spectroscope with 532nm & 785nm lasers, 0.75 cm-1 resolution, and 100-3500 cm-1 frequency range. XRD analysis utilized a Rigaku Smart Lab with PhotonMax 9kW rotating anode X-ray source and HyPix-3000 semiconductor, suitable for various sample types.

2.3 Fabrication of MWCNT-Silicone Rubber Composite Sheets

Silicone Rubber composites, ranging from 1% to 10% MWCNT by weight, were prepared by mixing 1kg of Silicone Rubber with varying MWCNT percentages for 30 minutes in two roll mill. The 6% dicumylperoxide was added as a curing agent. The Sheets were fabricated via compression molding at 200°C for 20 minutes, yielding 200mm x 200mm x 2.5mm dimensions [3].

2.4 ASTM Tests

The MWNT filled silicone rubber sheets were subjected to ASTM tests to assess their properties. Density (ASTM D 792) gauged mass per unit volume. Water absorption (ASTM D 570) evaluated resistance to moisture ingress. Tensile strength, hardness, tear strength, compressive strength, compression set, thermal expansion, thermal conductivity, TGA, and DSC tests provided comprehensive characterization.

3. Results and Discussion

3.1 XRD Anaysis

The XRD of MWCNT was shown in Fig.1. The sharp peaks indicates the crystallinity of MWCNTs. The high intensity of the (002) peak indicates the well alignment of MWCNTs on substrate surface. The peaks (002) at 25.9º and (100) at 43.3º were observed and well matched with previous results [25,26].

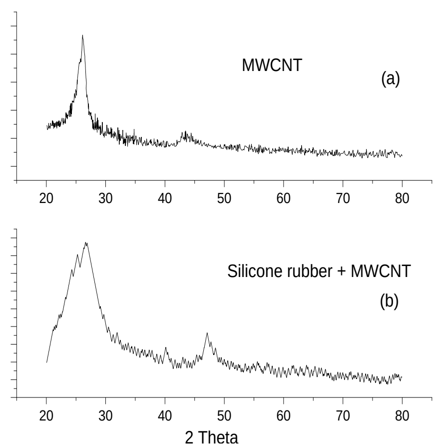

Figure 1. XRD of (a) MWCNTs (b) Silicone Rubber + MWCNTs

The X-ray diffraction (XRD) pattern for multi-walled carbon nanotubes (MWCNT) exhibits distinct characteristics that highlight their graphitic structure. A sharp peak at approximately $2\theta = 26°$ corresponds to the (002) reflection plane of graphitic carbon, indicative of the periodic arrangement of carbon atoms within the nanotube walls. This peak is associated with the interlayer spacing between the graphene sheets that form the nanotube structure. Additionally, the pattern may display a broad background or weaker peaks at higher angles, which signify the presence of disordered or amorphous carbon. Such features are typical of MWCNTs, especially when they contain structural defects or impurities. When MWCNT is incorporated into a silicon rubber matrix, forming a composite material, the XRD pattern undergoes notable changes. The (002) graphitic peak at $2\theta \approx 26°$ remains present but appears broader and less intense. This broadening is attributed to the dispersion of the nanotubes within the amorphous polymer matrix, which disrupts the overall crystalline order of the MWCNT. The reduction in the intensity of the peak further suggests strong interactions between the MWCNT and the silicon rubber, likely due to physical dispersion or chemical bonding. These interactions help integrate the nanotubes into the composite effectively.

The broad and less defined background observed in the composite's XRD pattern is characteristic of the amorphous nature of silicon rubber. Polymers like silicon rubber inherently lack long-range crystalline order, resulting in such broad XRD features. Despite the dominance of the amorphous phase, the retention of the graphitic peak from the MWCNT confirms that the nanotubes maintain the XRD analysis reveals that the incorporation of MWCNT into the silicon rubber matrix leads to a composite material with reduced crystallinity and strong interaction between the components. This structural modification suggests potential improvements in the material's properties, such as enhanced mechanical strength, thermal stability, and electrical conductivity.

3.2 FTRAMAN Anaysis

The Raman spectra of CSR and CSR+MWCNT provide valuable insights into the structural interactions within the polymer composite. The prominent peaks at 1311–1312 cm^{-1} (D-band) indicate defects or disordered carbon structures, while the peak at 1610 cm^{-1} (G-band) corresponds to graphitic or ordered sp^2 hybridized carbon. Additionally, the 2D bands observed at 2589 cm^{-1} (CSR) and 2616 cm^{-1} (CSR+MWCNT) highlight second-order Raman processes, reflecting graphitic carbon interactions. A slight shift in the D-band from 1311 cm^{-1} to 1312 cm^{-1} and in the 2D band from 2589 cm^{-1} to 2616 cm^{-1} in the CSR+MWCNT sample suggests significant interactions between the CSR matrix and MWCNTs, leading to structural modifications. The changes in peak intensities and shifts, particularly in the I^D/I^G ratio, indicate an increase in structural disorder and confirm the successful integration of MWCNTs into the CSR matrix. These interactions between CSR and MWCNTs are expected to enhance the composite's mechanical, thermal, and electrical properties, owing to improved load transfer, conductivity, and thermal stability. The Raman analysis thus validates the synergistic effects within the composite, offering potential for advanced performance in various applications.

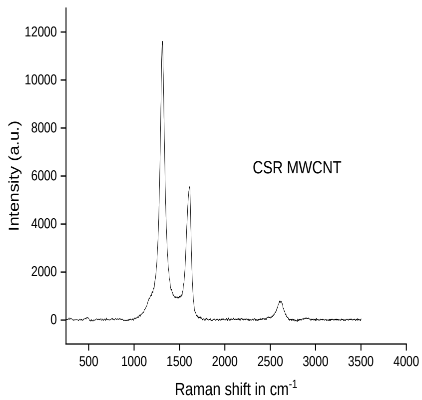

Figure 2. FT Raman of CSR + MWCNTs Composite

3.3 Elemental analysis

The elemental analysis of pure MWCNT was reported that 91.0 % of carbon and 1.1% of hydrogen. The Elemental analysis of The elemental analysis of single wall carbon nanotube soot was reported that 83.48% of Carbon and 0.7% of hydrogen [28]. The elemental analysis of Silicone rubber with MWCNT composites were carried and the weight% of carbon was observed 0.8%, 2.25%, 4.35% 6.1 and 8.90 % for 1%, 3%, 5%, 7% and 10% MWCNT loaded silicone rubber composites. The deviation of % of MWCNT might be the dispersion of MWCNT in Silicone rubber matrix.

3.4 Electron Microscopy analysis

The FESEM and TEM analyses highlights distinct yet complementary insights into the structural and compositional characteristics of the multi-walled carbon nanotubes (MWCNT) and silicon rubber composite. FESEM images provide a detailed visualization of the external morphology and dispersion of the MWCNTs within the silicon rubber matrix. At high magnification, the MWCNTs are observed as uniformly distributed thread-like structures with smooth surfaces and diameters ranging from 15 to 30 nm. The lower-magnification FESEM image corroborates the uniform embedding of MWCNTs, forming a network-like structure that reinforces the composite. Additionally, EDS mapping confirms the compositional uniformity, with carbon mapping indicating a consistent distribution of nanotubes and nickel mapping revealing minimal residual catalyst particles (below 30 nm), which do not adversely affect the material's properties.

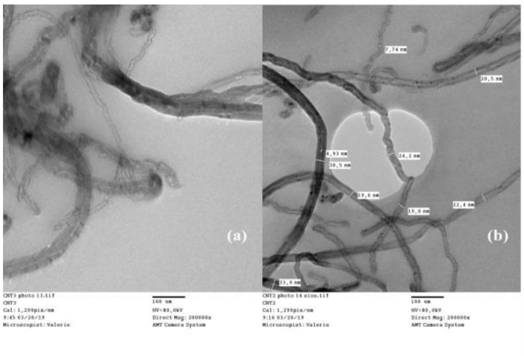

Figure 3. (a) FESEM images of MWCNT (b) FESEM image of MWCNT and corresponding elements mapping images (c) Carbon (d) Nickel

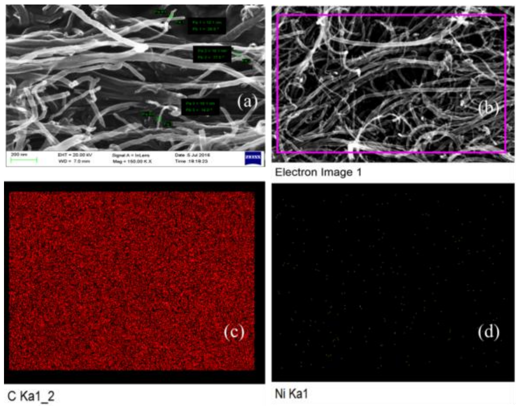

Figure 4. (a) and (b) HRTEM images of MWCNTs

TEM analysis, on the other hand, provides a complementary perspective by revealing the internal structure of the composite. The CNTs are observed in their characteristic cylindrical shape within the amorphous silicon rubber matrix. While TEM suggests effective dispersion of CNTs, it also identifies possible agglomerations that were not prominently detected in FESEM. TEM's ability to visualize at the nanoscale offers deeper insight into the interaction between CNTs and the polymer, shedding light on areas where dispersion may need optimization. Together, FESEM and TEM analyses confirm the composite's structural integrity and uniformity while emphasizing the critical role of uniform dispersion in achieving enhanced mechanical, thermal, and electrical properties.

3.5 Mechanical Properties

3.5.1 Hardness

The hardness of plain silicone rubber was initially observed to be around 53 on the shores scale. As the weight percentage of MWCNT increased from 1% to 7%, the hardness rose to 74 shores shows in Figure 5. The hardness of the silicone rubber composite with increase in wt% MWCNT was increased linearly due to the penetration of MWCNT in to the silicone rubber matrix [29]. However, with a further increase to 10% of MWCNT, the hardness slightly decreased to 70 shores. This might be due to the dispersion of MWCNT in silicone rubber matrix during the mixing in two roll mill. The room temperature vulcanized silicone rubber matrix the dispersion of higher content of MWCNT will increase the viscosity of silicone matrix result's the significant change of hardness was not observed [17].

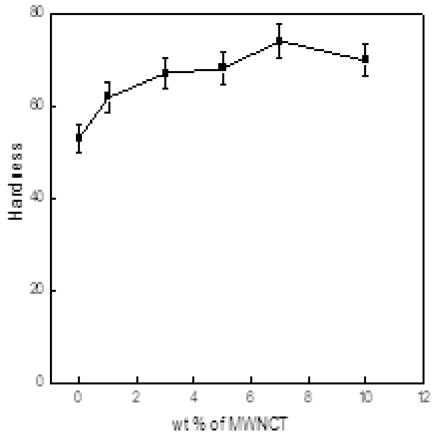

Figure 5. Hardness of Silicone rubber and MWCNT composite

3.5.2 Tensile Strength

The tensile strength of silicone rubber increased from 3.7 to 6.0 MPa with variations in the weight percentage of MWCNT shown in Figure 6. The surface area of MWCNT is high, resulting in a correspondingly high level of interaction between the MWCNT and silicone rubber. The storage modulus of the silicone rubber with MWCNT increases, when the wt% of WMCNT increased due to the hydrodynamic effect. At 10% MWCNT filler in silicone matrix, the strongest MWCNT-MWCNT network and at 1% MWCNT the weakest MWCNT-MWCNT network results the higher storage modulus and lower storage modulus [29].

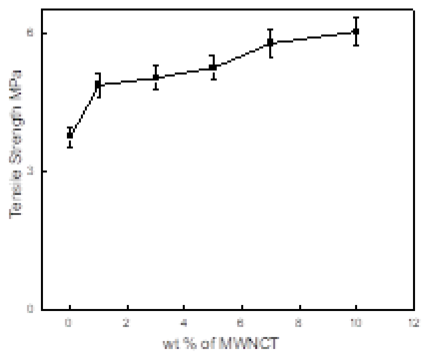

Figure 6. Tensile Strength of Silicone rubber and MWCNT composite

3.5.3 Compressive Strength

The compressive strength of composite comprising Silicone Rubber (SR) reinforced with multi-walled carbon nanotubes (MWCNT) is investigated in this work, along with the effects of MWCNT weight percentages (1%, 3%, 5%, 7%, and 10%) and tensile strength (1.8 MPa to 4.2 MPa). High tensile strength and stiffness are provided by MWCNT, which enhances silicone rubber, which is prized for its flexibility and longevity. The homogeneous dispersion of MWCNT and the strength of interfacial bonding determine the composites' compressive strength. Although reinforcing is enhanced by lower MWCNT concentrations, performance may be lowered by larger loadings due to agglomeration. The work aims to determine a relationship between tensile and compressive strength in order to optimise MWCNT concentration for balanced mechanical properties, with possible applications in biomedical devices, electronics, and structural components [30].

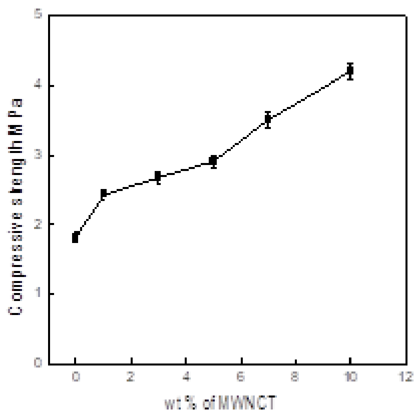

Figure 7. Compressive strength of Silicone rubber and MWCNT composite

3.6 Thermal Analysis

The Thermo Gravimetric Analysis curve for the MWCNT was shown in Figure 8. The curve reveals that the MWCNT is highly stable upto 700 ^oC.

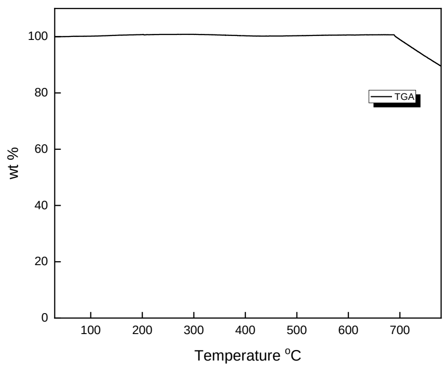

Figure 8. TGA of MWCNT

The high-shear mechanical mixing technique was used for dispersion of MWNCT in 1 to 20% wt%, with increase in CNT loading, increase in tensile strength, young's modulus, hardness was observed. The pyrolysis studies reveal's that the increase in CNT content the weight loss of the composite was decreased [28].

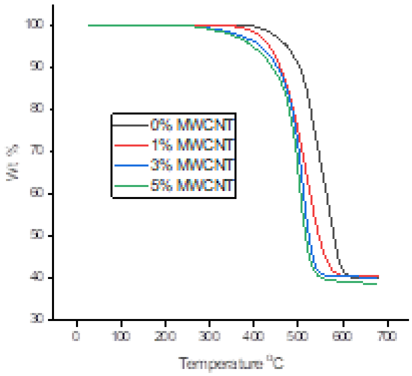

Figure 9. TGA of Silicone Rubber + MWCNTs

The TGA curves illustrate the thermal decomposition and stability of silicone rubber as the MWCNT concentration increases. The curve for 0% MWCNT (pure silicone rubber) likely shows the lowest thermal stability, with a more rapid weight loss onset and steeper decomposition phase due to the lack of reinforcing fillers. As the MWCNT content increases from 1% to 5%, the onset temperature of decomposition shifts to higher values, indicating improved thermal stability. This enhancement is attributed to the presence of MWCNT, which delays the breakdown of the polymer matrix by acting as a thermal barrier and improving the composite's structural integrity. Additionally, the residual mass at high temperatures increases with higher MWCNT loading, reflecting the presence of thermally stable carbon nanotubes in the composite. The curves demonstrate that the incorporation of MWCNTs improves the composite's resistance to thermal degradation, making it suitable for applications requiring higher thermal stability.

3.7 Thermal Conductivity

The effect of the weight percentage of MWCNT in the silicone rubber matrix is illustrated in Figure 10. The results indicate that as the weight percentage of MWCNT increases from 1% to 10%, the thermal conductivity rises from 0.32 to 0.581 W/mK.

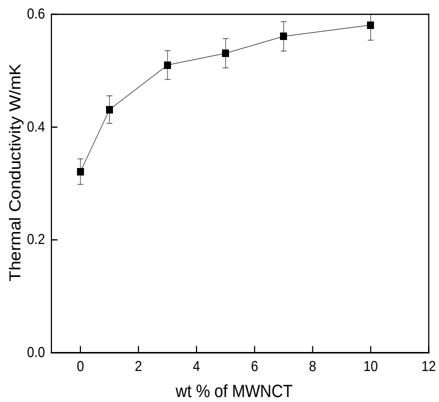

Figure 10. Thermal conductivity of Silicone Rubber + MWCNTs

The thermal conductivity linearly increases from 34% to 80%. This phenomenon depends on the phonon vibration, dispersion of MWCNT within the silicone matrix and Functionalization of MWCNT. The functionalization of MWCNT results the interfacial heat transport between MWCNT and silicone matrix [30].

4. Conclusions

The integration of multi-walled carbon nanotubes (MWCNT) into a silicone rubber (SR) matrix demonstrates significant potential for advancing sustainable building technology through enhanced structural, mechanical, thermal, and electrical properties. The XRD analysis revealed the retention of the graphitic (002) peak in composites, confirming the structural integrity of MWCNT, while its broadening indicated effective dispersion within the amorphous polymer matrix - characteristics crucial for long-term durability in building applications. Raman spectroscopy provided further evidence of strong interactions between the MWCNT and SR matrix, highlighted by shifts in the D and 2D bands and an increased I^D/I^G ratio, suggesting structural modifications that contribute to the composite's improved functionality in sustainable construction materials. The elemental and microscopy analyses corroborated the uniform distribution of MWCNTs in the matrix, with FESEM and TEM confirming the structural integrity and identifying areas for potential optimization in dispersion - factors essential for ensuring consistent performance in building components. The mechanical studies showcased a linear increase in hardness and tensile strength with MWCNT content up to an optimal loading, demonstrating potential for developing more durable and sustainable building materials that require less frequent replacement and maintenance.

Most significantly for sustainable building applications, thermal analysis illustrated that MWCNT incorporation substantially enhanced the thermal stability and conductivity of the composite. The increase in thermal conductivity with higher MWCNT loading, attributed to phonon vibrations and functionalization facilitating interfacial heat transfer, suggests promising applications in energy-efficient building designs. These improvements in thermal properties could contribute to reduced energy consumption in buildings through better thermal management, aligning with the growing demand for sustainable urban infrastructure. The developed SR/MWCNT composites thus represent a significant advancement in sustainable building technology, offering improved durability, enhanced thermal performance, and potential energy savings in urban development applications.

Declaration of Conflict of Interest: The research presented in this publication could not have been influenced by any known conflicts of interest, according to the authors.

Data Availability Statement: Data will be available on request.

References

[1] Guo L, Xu H, Wu N, et al. Molecular dynamics simulation of the effect of the thermal and mechanical properties of addition liquid silicone rubber modified by carbon nanotubes with different radii. E-Polymers. 2023;23(1).

[2] Yoshimura K, Nakano K, Nishiwaki T, et al. Effects of graded porous structures on the mechanical and electrical properties of Ketjenblack/silicone-rubber composites. Sensors and Actuators A: Physical [Internet]. 2021;332:113099.

[3] Jayakanth J, Chennakesavulu K, Reddy GR, et al. A study on development of silicone rubber with conductive carbon, polyaniline, MWCNT composite for EMI shielding. HIGH PERFORMANCE POLYMERS. doi: 10.1177/09540083221151013.

[4] Muslov SA, Polyakov DI, Lotkov AI, et al. Measurement and Calculation of Mechanical Properties of Silicone Rubber. Russian Physics Journal. 2021;63(9):1525–1529.

[5] Cho E, Chiu LLY, Lee M, et al. Characterization of mechanical and dielectric properties of silicone rubber. Polymers. 2021;13(11):1–18.

[6] Eung-Soo Kim, Hun-Sik Kim, Seong-Hun Jung jin-SY. Adhesion properties and thermal degradation of Silicone rubber. Journal of Applied Polymer Science. 2007;103:2782–2787.

[7] Ponnamma D, Sadasivuni KK, Grohens Y, et al. Carbon nanotube based elastomer composites-an approach towards multifunctional materials. Journal of Materials Chemistry C. 2014;2(40):8446–8485.

[8] Li ZW. Thermoelectric properties of carbon nanotube/silicone rubber composites. Journal of Experimental Nanoscience [Internet]. 2017;12(1):188–196.

[9] Bannych A, Katz S, Barkay Z, et al. Preserving softness and elastic recovery in silicone-based stretchable electrodes using carbon nanotubes. Polymers. 2020;12(6):1–11.

[10] Alam MN, Kumar V, Lee DJ, et al. Synergistically toughened silicone rubber nanocomposites using carbon nanotubes and molybdenum disulfide for stretchable strain sensors. Composites Part B: Engineering [Internet]. 2023;259(January):110759.
[11] Kim R, Roh S, Kim H. Investigation of relationship between carbon emission and building energy performance index for carbon neutrality. International Journal of Sustainable Building Technology and Urban Development. 2023;14(3):426–433.
[12] Kim R, Tae S, Lim H. Greenhouse gas emission analysis for each material composition of a cement reactive siloxane polymer-based penetration resist agent. International Journal of Sustainable Building Technology and Urban Development. 2019;10(3):167–175.
[13] Kwon SK, Ahn JM, Kim GH, et al. Microwave absorbing properties of carbon black/silicone rubber blend. Polymer Engineering and Science. 2002;42(11):2165–2171.
[14] Zhao XW, Zang CG, Wen YQ, et al. Thermal and mechanical properties of liquid silicone rubber composites filled with functionalized graphene oxide. Journal of Applied Polymer Science. 2015;132(38):1–10.
[15] Nosbi N, Akil HM. Thermal properties of multiwalled carbon nanotubes-alumina (MWCNT-Al2O3) hybrid filled silicone rubber composites. Advanced Materials Research. 2014;844:330–333.
[16] Song Y, Yu J, Yu L, et al. Enhancing the thermal, electrical, and mechanical properties of silicone rubber by addition of graphene nanoplatelets. Materials and Design [Internet]. 2015;88:950–957.
[17] Li P, Duan HY, Liu YF, et al. Multi-walled carbon nanotubes as secondary fibre fillers for property improvement of short carbon fibre-reinforced silicone rubber. Bulletin of Materials Science. 2019;42(4):1–8.
[18] Mazlan N, Jaafar M, Aziz A, et al. Effects of different processing techniques on multi-walled carbon nanotubes/silicone rubber nanocomposite on tensile strength properties. IOP Conference Series: Materials Science and Engineering. 2016;152(1).
[19] Yang J, Liao X, Li J, et al. Light-weight and fl exible silicone rubber / MWCNTs / Fe 3 O 4 nanocomposite foams for e ffi cient electromagnetic interference shielding and microwave absorption. Composites Science and Technology [Internet]. 2019;181(January):107670.
[20] Lee B, Yoo H. Effects of Carbon Black on Mechanical Properties and Oil Resistance of Liquid Silicone Rubber. 2024;
[21] Eung Soo Kim, Tae Hwa Lee, Eun Jeong Kim J-SY. Surface modification of carbon fiber and the mechanical properties of the silicone rubber/carbon fiber composites. Journal of Applied Polymer Science. 2012;126:E410–E418.
[22] J. J. Wang, La-Jun Feng, A.-Li Lei, Ai-Jun Yan X-JW. Thermal Stability and Mechanical Properties of Room Temperature Vulcanized Silicone Rubbers. Journal of Applied Polymer Science. 2012;125:505–5011.
[23] Ramanjaneya Reddy G, Balasubramanian S, Chennakesavulu K. Zeolite encapsulated Ni(ii) and Cu(ii) complexes with tetradentate N 2O2 Schiff base ligand: Catalytic activity towards oxidation of benzhydrol and degradation of rhodamine-B. Journal of Materials Chemistry A [Internet]. 2014;2(37):15598–15610.
[24] Yang Z, Xia Y, Mokaya R. Aligned N-doped carbon nanotube bundles prepared via CVD using zeolite substrates. Chemistry of Materials. 2005;17(17):4502–4508.
[25] Nie P, Min C, Song HJ, et al. Preparation and tribological properties of polyimide/carboxyl-functionalized multi-walled carbon nanotube nanocomposite films under seawater lubrication. Tribology Letters. 2015;58(1):1–12.
[26] Aqel A, El-Nour KMMA, Ammar RAA, et al. Carbon nanotubes, science and technology part (I) structure, synthesis and characterisation. Arabian Journal of Chemistry [Internet]. 2012;5(1):1–23.
[27] Elizabeth I. Braun and Paul Pantano. The importance of an extensive elemental analysis of single wall carbon nanotube soot. Carbon. 2014;77:912–919.
[28] Katihabwa A, Wang W, Jiang Y, et al. Multi-walled carbon nanotubes/silicone rubber nanocomposites prepared by high shear mechanical mixing. Journal of Reinforced Plastics and Composites. 2011;30(12):1007–1014.
[29] Li Y, Li M, Pang M, et al. Effects of multi-walled carbon nanotube structures on the electrical and mechanical properties of silicone rubber filled with multi-walled carbon nanotubes. Journal of Materials Chemistry C [Internet]. 2015;3(21):5573–5579.
[30] Kong KTS, Mariatti M, Rashid AA, et al. Effect of processing methods and functional groups on the properties of multi-walled carbon nanotube filled poly(dimethyl siloxane) composites. Polymer Bulletin. 2012;69(8):937–953.