Amino-Functionalized MWCNT/Ecoflex Nanocomposites for Stimuli-Responsive Soft Robotic Actuation and Interfaces

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INTRODUCTION & AIM

Capacitance and dielectric properties play a vital role in soft robotics, where many actuators and sensors rely on the interaction between electric fields and flexible materials. Selecting materials with suitable dielectric behavior allows soft robots to become more responsive, energy-efficient, and safe during operation. Among flexible materials, silicone-based composites are widely used because of their elasticity, stability, and compatibility with conductive fillers. Incorporating amino-functionalized multi-walled carbon nanotubes (Amino-MWCNTs) into silicone elastomers such as Ecoflex can significantly enhance their electrical and thermal properties, enabling tunable capacitance and improved electromechanical performance. Understanding both capacitance and Joule heating characteristics is essential for developing self-sensing and self-heating components in next-generation soft robotic systems.
The goal of this study is to investigate the capacitance and Joule heating behavior of Amino-MWCNT–Ecoflex nanocomposites, aiming to enhance their potential use as self-sensing and self-heating materials for soft robotic applications.

METHOD

Amino-MWCNTs (0.25–1 wt%) were mixed with Ecoflex 30, dispersed in Part A, then Part B was added (1:1 ratio). The mixture was poured into molds, cured at room temperature (6 h), demolded, and checked for uniformity (Fig. 1).A capacitance measurement device was designed using the Amino-MWCNT–Ecoflex nanocomposite as a dielectric between two aluminum plates, with capacitance measured in nF by a digital multimeter (Fig. 2).The 246 nF capacitor was connected in series with a 1 kΩ resistor to measure AC current (1 kHz) and temperature at one-minute intervals for each voltage (Fig. 3).

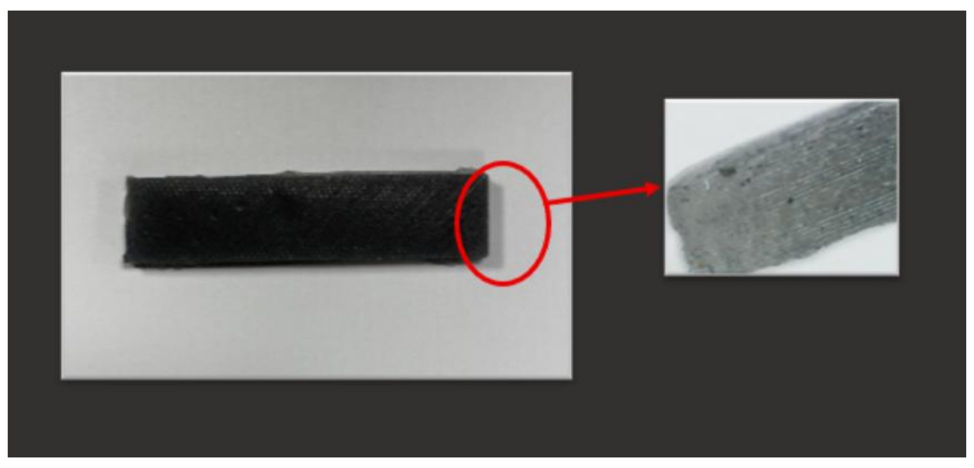


Fig.1. 0.25 wt% Amino-MWCNT–Ecoflex molded and cured

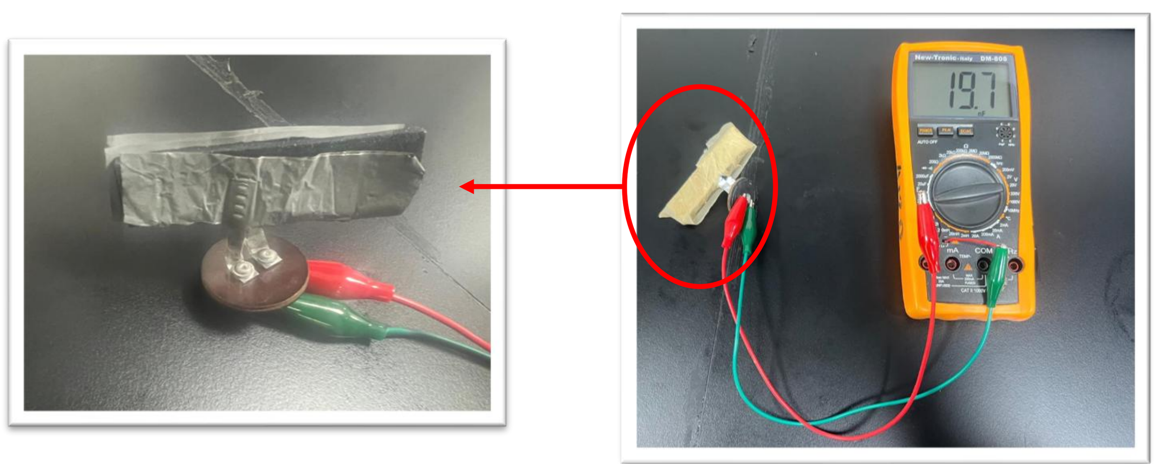


Fig. 2. Capacitance setup with Amino-MWCNT–Ecoflex dielectric.

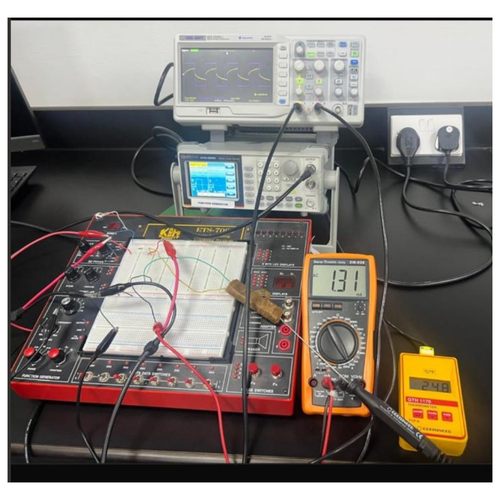
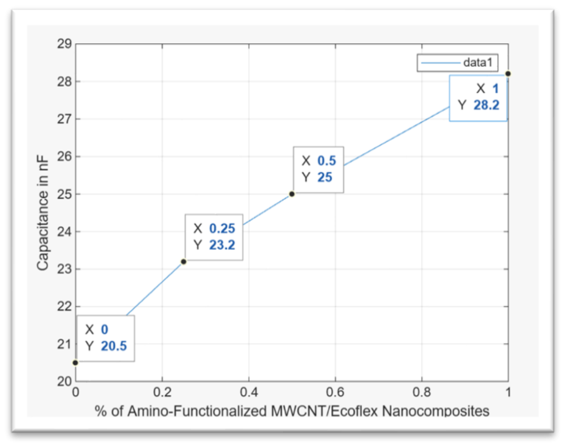


Fig. 3. AC test setup of Amino-MWCNT–Ecoflex capacitor with 1 kΩ resistor.

RESULTS & DISCUSSION

1. Capacitance and Permittivity:

Sample composition: % CNT	Dielectric Dimension			Capacitance measured	Area (m^2)	ε_r (calculated)
	Length	Width	Thickness			
0%	69 mm	15 mm	4 mm	20.5 nF	1.035×10^{-3}	8.9
0.25%	69 mm	15 mm	5 mm	23.2 nF	1.035×10^{-3}	12.6
0.50%	66 mm	16 mm	4 mm	25 nF	1.056×10^{-3}	10.7
1.00%	70 mm	15 mm	6 mm	28.2 nF	1.05×10^{-3}	15.1

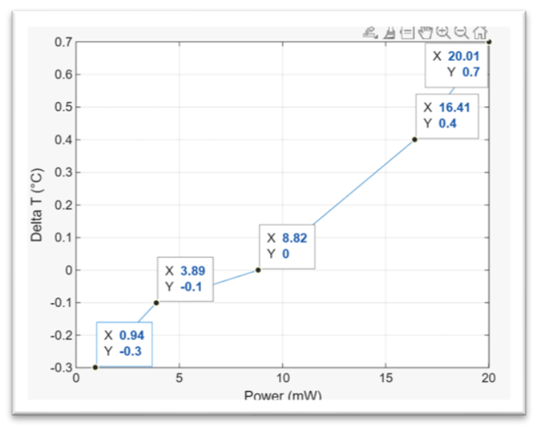


The capacitance increased from 20.5 nF (0% CNT) to 28.2 nF (1% CNT), indicating improved charge storage with higher CNT content. The calculated relative permittivity (εr) rose from 8.9 to 15.1, confirming that Amino-MWCNTs enhanced the dielectric constant of the Ecoflex matrix. This improvement is attributed to better polarization and conductive network formation within the silicone composite. The steady rise in εr with CNT loading suggests effective filler dispersion and strong interfacial interaction, which support higher energy density and sensitivity for soft actuator or sensor applications.

2. Thermal characterization (Joule heating)

Thermal Conductivity Test

Vc(Vp)	Vc(Vrms)	Current (mA)	Power (mW) = V × I	Initial Temp (T_0, °C)	Final Temp (T_1, °C)	$\Delta T = T_1 - T_0$ (°C)
1	0.707	1.33	0.94	25.2	24.9	-0.3
2	1.414	2.75	3.889	24.8	24.7	-0.1
3	2.121	4.16	8.824	24.7	24.7	0
4.16	2.941	5.58	16.413	25.2	25.6	0.4
4.5	3.181	6.29	20.014	25.1	25.8	0.7



As the applied voltage increased from 1.0 to 4.5 V, both current and power rose correspondingly, producing a small but consistent temperature increase (ΔT = 0.3–0.7°C). This demonstrates the Joule heating effect of the conductive network formed by Amino-MWCNTs. The slight temperature rise under low voltage confirms safe and stable electrothermal behavior, suitable for self-heating or temperature-responsive functions in soft robotics.

CONCLUSION

Amino-MWCNT–Ecoflex nanocomposites demonstrated enhanced dielectric and electrothermal performance suitable for soft robotics. The dielectric constant increased with CNT loading, indicating improved polarization and charge storage capability. Joule heating tests showed a gradual temperature rise with increasing voltage, confirming stable and controllable thermal response. These results highlight the potential of Amino-MWCNT composites for developing self-sensing, energy-efficient, and thermally adaptive soft robotic systems.

SELECTED REFERENCES

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