

Electronically Conducting Carbon Black/ PVDF-HFP Membrane for the Improved Load-Bearing Property of Electroadhesive Clutches

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Abstract

Electroadhesive clutches have demonstrated promising benefits in various gripping applications. This work presents a safe, easy-to-assemble, lightweight, flexible electroadhesive (EA) actuator/clutch that can be operated with low power consumption. To enhance the load-bearing execution of the electroadhesive clutches, an electronically conducting membrane was introduced between the dielectric layer and the electrode. The electronically conducting layer was made by incorporating carbon black in the PVDF-HFP polymer grid and fabricated into films by the doctor blade method in different proportions. The XRD and SEM analyses are carried out to determine the structural information and morphology of the fabricated films. The dielectric, resistivity, conductivity and electrical properties of the films were also tested. Experimental evidence suggests that at 98 V, the actuator can support a 550 g load for a clutch pair with a 6 x 2 cm² dielectric layer overlap. The conductivity of PCB0.5, PCB1, and PCB1.5 was found to be 0.0048 mS cm⁻¹, 0.0106 mS cm⁻¹, and 0.0438 mS cm⁻¹. This study offers a potentially useful application in rehabilitation, geriatric healthcare, robotic mechanisms, etc.

Keywords- PVDF-HFP, Carbon black, Flexible electroadhesive actuator, Polymer composite.

1. Introduction

Adhesion is a process of attachment of a surface to another surface (Vert et al., 2012). The attractive force that develops between two surfaces when a potential difference is applied between them is known as electroadhesion. The two distinct clutch plates make up the electroadhesive (EA) clutch/actuator (West et al., 2020). Numerous gripping methods have been developed using EA clutches/actuators including those used in rehabilitation (Feizi et al., 2022), teleoperation (Ramachandran et al., 2022), robotic mechanisms (Levine et al., 2022), geriatric healthcare (Sposito et al., 2022), etc. Due to its flexibility and less weight, EA clutches/actuators are primarily designed for wearable applications (Diller et al., 2018). Research on electroactive dielectric polymer films is currently very active on a global basis. The wide range

of applications of fluoropolymers like polyvinylidene difluoride (PVDF), polyvinylidene fluoride-trifluoro ethylene (PVDF-TrFE), and poly (vinylidene fluoride-hexa-fluoropropylene) (PVDF-HFP) has resulted in their significance in the market (Chatterjee et al., 2021). These materials have a growing number of applications in energy storage, sensors, actuators, and other devices (Xia & Zhang, 2018). In particular, PVDF-HFP is more affordable and has better mechanical strength, solubility, and hydrophobicity properties and has received more scientific and technical consideration than other fluoropolymers like PVDF and PVDF-TrFE (Wu et al., 2014). Semi-crystalline nature of PVDF-HFP exhibits uneven structural polarizabilities (Zhu et al., 2023), which is the primary reason for adhesion. The present work uses PVDF-HFP as the polymer grid to make electroadhesive tape as an electronically conducting material. Many areas of the electronics marketplace are interested in polymeric composites filled with conductive fillers, including optoelectronics, energy storage devices, photovoltaic devices, etc (Yan et al., 2023). Carbon black (CB) is frequently used to enhance the mechanical and electrical characteristics of polymers due to its good interaction between the Carbon black particles and the polymer grids (Moezzi et al., 2019). In general, the higher conductivity of CB leads to a higher dielectric constant in any polymer composites (Rani et al., 2020). Though the PVDF-HFP polymer is an insulator, in the present work, the polymer was turned into an electronically conducting tape by incorporating CB, and we have demonstrated a new application of the tape by exploring it as an interface between the electroadhesive tape and the Cu-Ni fabric.

Ranjithkumar et al.(2023a) reported the influence of 2D-hexagonal Boron nitride (hBN) on electroadhesive applications. For rapid adhesion at low voltage, the tapes must have strong dielectric polarizability, as the authors found in the case of 2D-hBN/PVDF-HFP composite electroadhesive tapes. The EA actuator was found to bear a load of 100 g at a minimum adhesion voltage of 130 Volts. But, for applications like haptic devices, rehabilitation, or any other applications with human contact, the efficiency of the EA actuator has to be further enhanced (Ranjithkumar et al., 2023a). Furthermore, the author claimed that PVDF-HFP with hBN/Barium titanate composite improves load-bearing ability (Ranjithkumar et al., 2023b). The authors achieved a 4 times higher efficiency than in their prior work. It was found to bear a load of 350 g at a minimum adhesion voltage of 138 Volts.

The higher the load-holding property of the electroadhesive actuator at minimum voltage, the higher its efficiency for gripping applications. When it can withstand a high load at a minimum voltage, it can be used in human-wearable applications. Electroadhesive clutches have emerged as a promising solution for load-bearing applications due to their ability to generate high holding forces using polymer composite materials. At the same time, the EA actuators should be made in an easy-to-assemble approach. In the current work, 2D one-hour ball-milled hBN/PVDF-HFP composite tape, CB/PVDF-HFP composite membrane, and Cu-Ni conducting fabric are used to design the EA clutch. The present research work is aimed at improving the load-carrying capacity of the EA actuator at a minimum adhesion voltage by introducing an electronically conducting membrane as an electron-storing medium at the interface between the electroadhesive tape and the Cu-Ni conducting fabric tape. The presence of the electron-storing medium has improved the load-bearing capacity and reduced the adhesion voltage to a greater extent. The making of the electronically conducting membrane and its role in improving the load-bearing property of the EA actuator are presented in detail.

2. Experimental Methods and EA Actuator

2.1 Materials

N, N-Dimethylformamide (DMF of mw = 73.09 g/ml), Poly (vinylidene fluoride co-hexafluoropropylene) (PVDF-HFP of mw = 400,00), and Carbon black (CB of mw = 12.011 g/mol) were purchased from Sigma-Aldrich and were used for the fabrication of electroadhesive tapes.

2.2 Preparation of PVDF-HFP/CB Electronically Conducting Tape

To make the electronically conducting tape, PVDF-HFP (4 grams) was first dissolved in DMF solution (30 ml) and blended at 500 revolutions per minute for 4 hours in the magnetic stirrer. Then, 1 g of CB was added and stirred into the above liquid mixture for 24 hours to produce a homogeneous solution. The homogeneous solution was then dispersed well using an ultrasonic processor: Oscar/PR-250 MP for 15 minutes and then stirred again for 15 minutes in a magnetic stirrer. The homogeneous solution was then cast on the aluminium tape over the glass substrate using the doctor blade coating method with uniform thickness. The casted solution was then desiccated in the vacuum oven for 4 hours. Later, the electronically conducting tape was stripped from the substrate and stored for further characterization studies. For comparison, the bare PVDF-HFP (PP) tape was also fabricated by dissolving four grams of PVDF-HFP in 30 ml DMF solvent solution and coated by the doctor blade coating technique, as shown in **Figure 1**.

The sample code for the above electronically conducting membrane was given as PCB1. A similar procedure was repeated for the membranes PCB0.5 and PCB1.5, which were made with 0.5 g and 1.5 g of CB, respectively. The images of the fabricated membranes: PP, PCB0.5, PCB1, and PCB1.5 are given in **Figure 2**. The insulating bare PVDF-HFP membrane was found to be smooth and transparent. While PCB1 and PCB0.5 were found to be defect-free, the conducting tape PCB1.5 was found to have an uneven distribution of CB with more pinholes. Even after repeating the procedure for PCB1.5, the uneven distribution and the presence of pinholes suggest the threshold limit of the CB in the PVDF-HFP grid for the fixed polymer wt%.

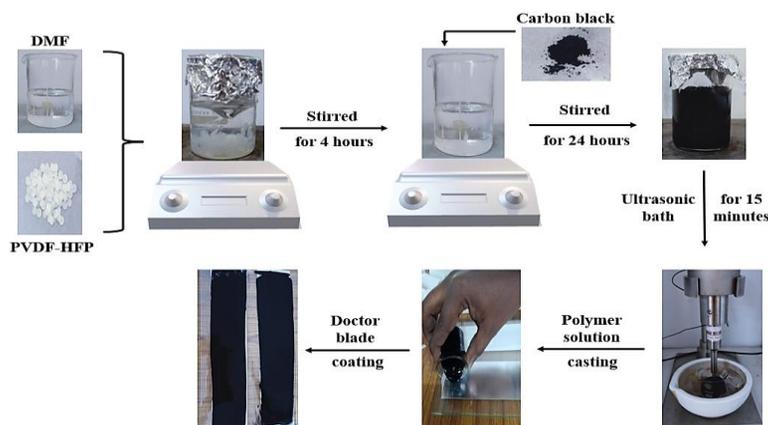


Figure 1. Schematic of the preparation of the CB/PVDF-HFP electronically conducting membrane.

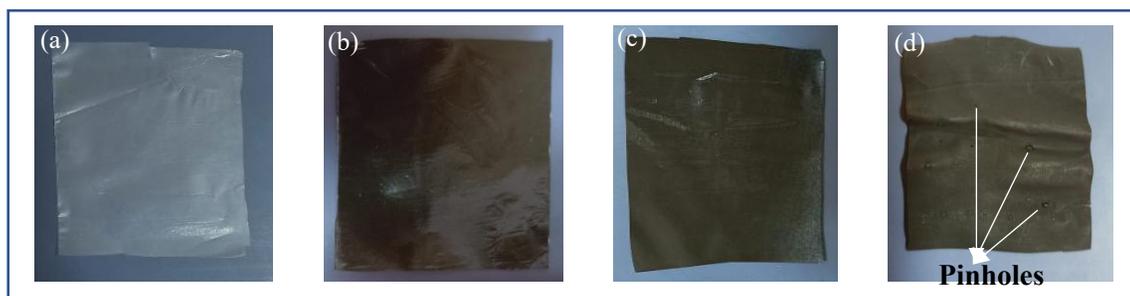


Figure 2. Image of the fabricated tapes: (a) PP, (b) PCB0.5, (c) PCB1, and (d) PCB1.5.

2.3 EA Device Design and Making of the EA Actuator

The most common EA actuator design uses two coplanar electrodes contacted with the dielectric medium. Two conductive pads that may withstand a voltage difference between them make up electroadhesive clutches (Guo et al., 2020). An EA device requires the following components: dielectric tape, an electronically conducting membrane, a current collector, a DC-DC booster circuit, and a voltage control unit. Maximum load-bearing capability with the consumption of low voltage can be achieved by the use of a DC-DC booster circuit with a voltage-controlling unit. The schematic representation of an EA device design and EA clutch is shown in **Figure 3** and **Figure 4**.

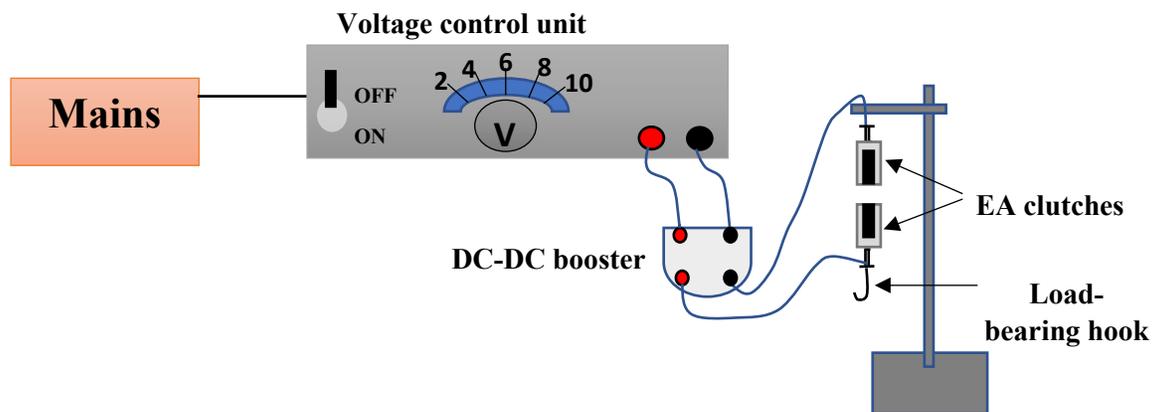


Figure 3. The schematic of an EA device design.

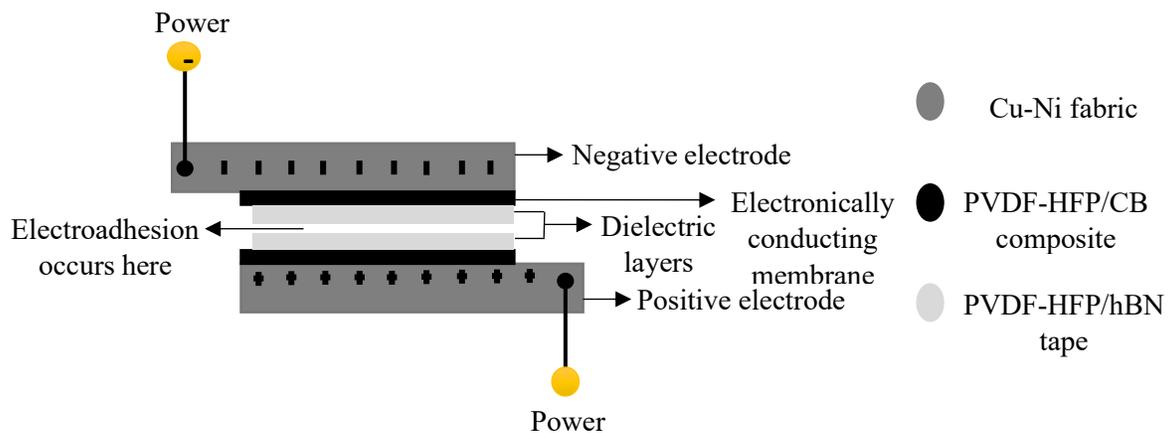


Figure 4. Transverse view EA actuator/clutch.

The electrostatic attraction does not exist between the electrodes when there is no potential differential between them. In contrast, the electrodes are drawn together by electrostatic attraction when a voltage is applied. Soft polymeric materials are excellent choices for electroadhesive clutches (Zhai et al., 2021). Therefore, the purpose of this work is to boost the load-holding capacity of the electroadhesive clutches by

adding an electronically conducting polymer membrane between the dielectric polymer tape and the conducting fabric electrode. To make the electroadhesive actuator, the electroadhesive tape (PBN) was prepared using PVDF-HFP and 2D one-hour ball-milled hBN as reported by Ranjith Kumar et al (Ranjithkumar et al., 2023a). The electroadhesive tape (dielectric layer) with a cross-sectional area of $6 \times 2 \text{ cm}^2$ is pasted over the prepared electronically conductive tape having a cross-sectional area of $5 \times 1.5 \text{ cm}^2$. Cu-Ni fabric is fixed above the electronically conducting tape to ensure the flow of electrical charges. Three different electroadhesive actuators are made using PCB0.5, PCB1, and PCB1.5 membranes and are named: EA0.5, EA1, and EA1.5.

3. Characterization Techniques

The X-ray diffraction tests were carried out using the SHIMADZU-XRD 6000 diffractometer, which has a scanning range of 5-80 (degrees) and a Cu-K radiation source operating at 40 kV. All the materials were characterized using a scan speed of 10° per minute, and the outcomes were compared to standard JCPDS data. Morphological analysis was performed using the JEOL-JSM-6000 Scanning Electron Microscope (SEM). The Four Probe Set-up FPA-RM analyses the resistivity of the sample. The CH electrochemical workstation (CHI-6008E) was used to examine the electrochemical studies of the samples.

4. Results and Discussions

4.1 X-Ray Diffraction (XRD) Analysis

X-ray diffraction studies were performed to determine the semi-crystalline and crystalline nature of the fabricated tapes. The XRD pattern of the PP is given in **Figure 5(a)**. The 2θ peaks at 18° , 20° , and 24° correspond to hkl planes of (0 2 0), (2 0 0), and (0 2 2), respectively, confirming the presence of PVDF-HFP copolymer as reported in the literature (Peng et al., 2014). The presence of broad peaks indicates the semi-crystalline nature of the PVDF-HFP copolymer, which denotes the incomplete crystallization of PVDF units in its copolymer and results in a semi-crystalline structure.

XRD profiles of CB nano powder and electronically conducting PVDF-HFP/CB membranes PCB0.5, PCB1, and PCB1.5 show a blend of crystalline and semi-crystalline nature of membranes as shown in **Figure 5(b)**. According to JPCDS card number 74-2330, the 2θ peaks around 37.8° , 44.1° , 64.5° , and 77.7° belonging to (h k l) planes (0 0 12), (1 1 4), (0 0 2), and (1 3 0) planes confirm the presence of CB nano powder in the polymer membrane composite. The 2θ peak around 25° corresponds to the (h k l) plane (0 0 2), indicating the amorphous carbon peak, suggesting the presence of disordered carbon instead of a well-defined crystalline structure as reported previously in the literature by Rajan et al. (2014). The broad (002) peak around 25° in PCB1.5 and CB is a characteristic feature of carbon black. In PCB0.5 and PCB1, the CB nanoparticles are well dispersed in the PVDF-HFP matrix, so individual particles are isolated, and the weak CB signal is obscured by the polymer peaks. At higher loading (PCB1.5), CB particles begin to agglomerate, forming coherent domains that produce a detectable (002) peak. The broad nature of the peak confirms the disordered structure of CB and indicates partial aggregation at higher loading, consistent with the observed improvement in electrical conductivity. The carbon black CB integrated with PVDF-HFP displays modified peak locations in all PVDF-HFP/CB composite membranes. The main peaks experienced a shift from $2\theta = 18^\circ$, 20° to new positions after the introduction of CB into the PVDF-HFP system. Also, the magnitude of the peaks increases with a higher incorporation of CB.

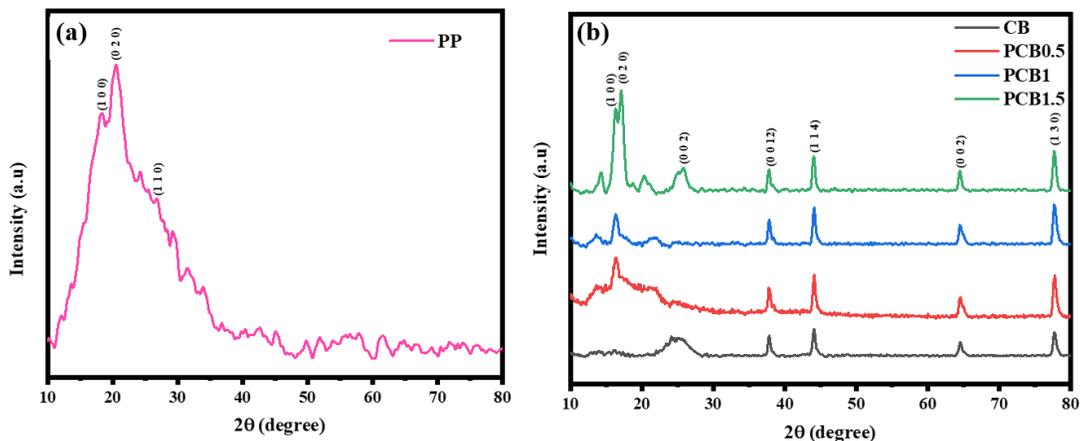


Figure 5. XRD pattern of (a) bare PVDF-HFP tape, (b) CB powder, and different compositions of PVDF-HFP/Carbon black composite membranes.

4.2 Fourier Transform Infrared Spectroscopy (FTIR)

The qualitative analysis of surface functional groups was carried out using FTIR spectroscopy within the range of 4000 to 400 cm^{-1} . **Figure 6** illustrates the results of the FTIR analysis and the assignment of peaks for various surface functional groups. The absorption bands at 3857 cm^{-1} are primarily associated with the hydroxyl group (Li et al., 2020). The prepared membranes exhibit a common peak, positioned at 2314 cm^{-1} , attributed to the CO_2 signal supporting the incorporation of carbon into the polymer matrix (Choudhary & Pramanik, 2019). The peaks at 1728 and 1505 cm^{-1} are due to the wagging and scissoring vibration of vinylidene, while peaks at 671 and 478 cm^{-1} are attributed to CF_2 vibrations (Shanthi et al., 2018). Therefore, peaks showed the presence of CB and PVDF-HFP functional groups, indicating the membrane is made with the blend of PVDF-HFP/CB composite.

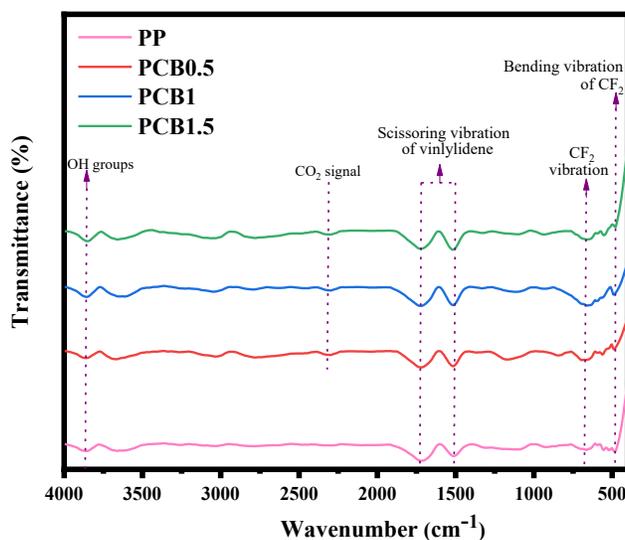


Figure 6. FTIR spectra of bare PVDF-HFP and PVDF-HFP/CB composite membranes.

4.3 Scanning Electron Microscope (SEM) Analysis

Figure 7 displays the surface morphology of bare PVDF-HFP and CB/PVDF-HFP composite polymer membranes. The surface of bare PVDF-HFP was found to be smooth, and the surface morphologies of PCB0.5, PCB1, and PCB1.5 were found with the presence of CB particles in the PVDF-HFP grid. In the case of PCB0.5, it was found that the presence of CB particles is very low, while in the case of PCB1.5, the particles are agglomerated. As the presence of CB particles is higher in this case, more electron accumulation will lead to current leakage. Thus, for EA applications with an increase in voltage, the electronically conducting PCB1.5 membrane may be damaged due to current leakage. It was found that CB nano powder interacts well with the polymer grid in the case of PCB1. The incorporation of 1g of CB into PVDF-HFP results in the optimum fabrication of the composite polymer, making it well-suited for use in load-bearing electroadhesive actuators.

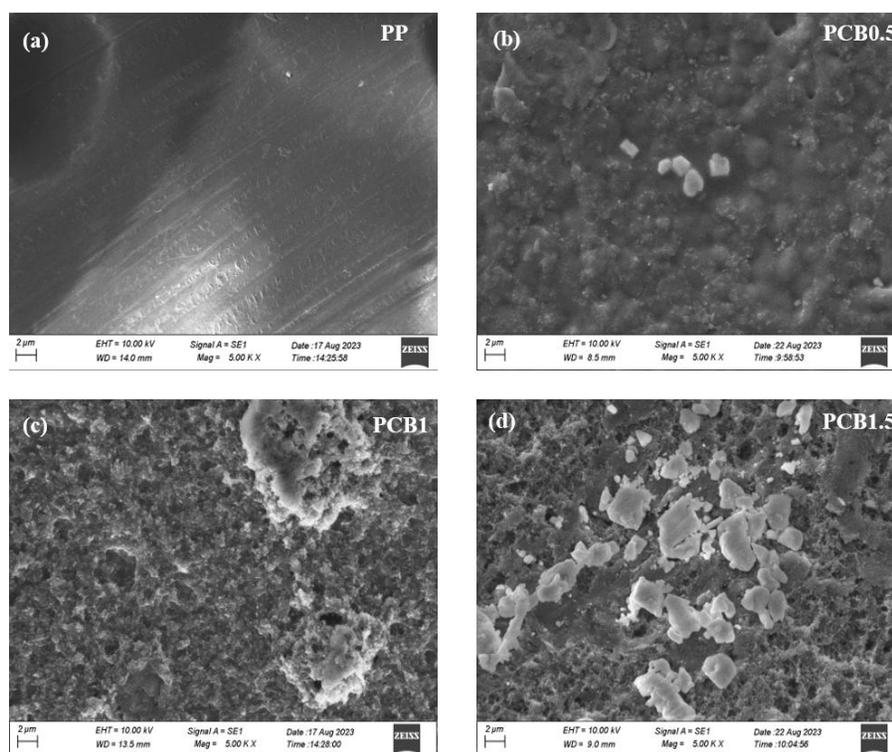


Figure 7. The surface morphology of (a) bare PVDF-HFP film, (b) PCB0.5, (c) PCB1, and (d) PCB1.5.

4.4 Electrical Studies

Four-Probe Method

The four-probe measurements were done to determine the electrical resistivity and conductivity of the fabricated membranes. In the setup, the four probes were placed evenly on each fabricated polymer membrane, with two outer tips facilitating the flow of current and the inner two tips measuring voltage, allowing for precise electrical resistance and conductivity measurement. The measurements were carried out at room temperature by applying the current (1 – 10 mA), and the corresponding voltage was measured.

Figure 8 shows the V-I characteristic plot for the samples: PCB0.5, PCB1, and PCB1.5. The electrical resistivity “ ρ ” and electrical conductivity “ σ ” of the material were found by equation (Waremra & Betaubun, 2018):

$$\rho = 2\pi s \frac{V}{I} \tag{1}$$

where, s , V , and I represent the equidistance of the probes ($s = 2$ mm), the potential difference between the inner two probes, and the current passing through the two outer tips. The electrical conductivity, σ was further calculated using:

$$\sigma = \frac{1}{\rho} \tag{2}$$

The electrical studies confirm the diverse changes in the electrical resistivity of the membranes due to the different amounts of CB in the polymer matrices. It was found that the resistivity of electronically conducting tapes PCB0.5, PCB1, and PCB1.5 was found to be 204.3 Ω cm, 93.8 Ω cm, and 22.7 Ω cm, respectively. Furthermore, the conductivity of PCB0.5, PCB1, and PCB1.5 was found to be 0.0048 mS cm^{-1} , 0.0106 mS cm^{-1} , and 0.0438 mS cm^{-1} . This reveals that the conductivity of polymer membranes increases with increases in CB content.

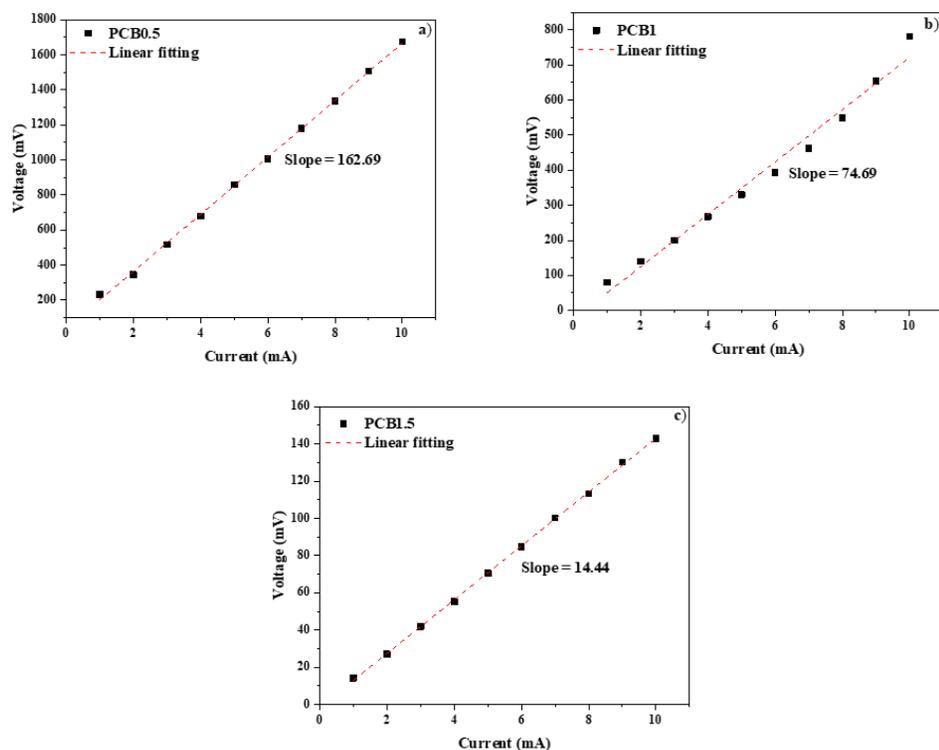


Figure 8. V-I characteristics of the conducting membranes.

AC Impedance

The electrical studies of the electronically conducting tapes were measured using Cu-Ni tape as leads by an AC impedance analyser at a frequency ranging from 1 MHz to 1 Hz with an amplitude of 0.025 V at room temperature. **Figures 9(a)** and **9(b)** represent the dielectric constant and dielectric loss of the fabricated membranes. The dielectric constant and loss are critical in determining the electrical conductivity of a dielectric membrane. The dielectric constant plot reveals the ability of the material to store charge in an electric field. In contrast, the dielectric loss spectra present the energy loss of the polymer when an electric

field is applied (Das et al., 2018). The dielectric behaviour of the composites decreases with an increase in frequency. Based on the analysis, it is evident that PCB1.5 possesses the highest dielectric constant compared to PCB1 and PCB0.5.

Concerning the dielectric loss plot, it is evident that PCB1.5 displays the highest value and shows greater energy loss. By adding carbon black to the polymer matrix, composites exhibit an increase in dielectric loss because of the increased number of charges in the system, as indicated by the variance in dielectric behaviour. A good electrically conducting membrane requires a suitable balance between the two qualities. It is crucial to carefully regulate the quantity of carbon black added to the polymer matrix to minimize the dielectric loss to maximize the composite material's performance. **Figure 9(c)** represents the conductivity plot of fabricated membranes. The composition of the conducting material determines the conductivity of the polymer membrane. A higher carbon content confers greater conductivity, which allows the membrane to store charges more effectively. The maximum conductivity is seen from PCB1.5, followed by PCB1 and PCB0.5, indicating the correlation between carbon black content and conductivity. The dissipation factor or tangential loss measures energy loss within a sample. It is defined as the proportion of energy lost (dielectric loss) to energy stored (dielectric constant) in an electric field (Sanjay et al., 2023). As the frequency rises, a decline in tangent loss is shown for every sample. Among the three membranes, PCB1 possesses the lowest tangent loss as shown in **Figure 9(d)**. At low carbon black levels (PCB0.5), the limited number of conductive pathways leads to lower charge storage and loss. With increasing filler concentration (PCB1), polarization improves, resulting in a higher dielectric constant and conductivity but a reduced tangent loss due to balanced charge distribution. For the highest loading (PCB1.5), the formation of continuous conductive networks enhances dielectric loss and conductivity, while the tangent loss decreases slightly due to more efficient charge relaxation. Overall, PCB1 provides the ideal properties for electroadhesive applications as an electroadhesive clutch must have a moderate dielectric constant, a reduced dielectric loss, minimum tangent loss, and superior conductivity in its electrically conductive membrane.

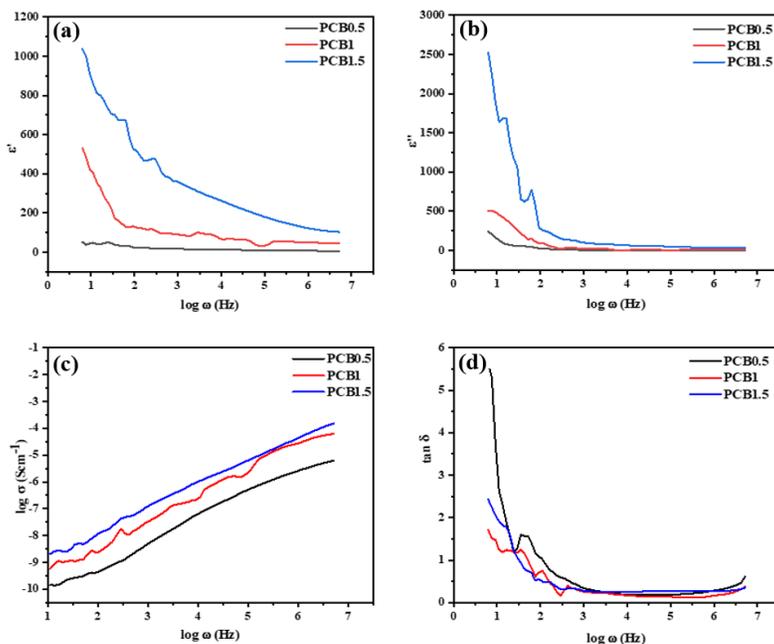


Figure 9. Variations of electrical studies of PCB0.5, PCB1, and PCB1.5 membranes: (a) dielectric constant, (b) dielectric loss, (c) conductivity plot, (d) tangent spectra.

4.5 Thermal Conductivity

To determine the ability of the electroadhesive clutch to function in a high-temperature robotic mechanism, the thermal conductivity of the polymer membrane was also measured. The transient hot wire method is used to analyze the thermal conductive properties of the prepared polymer membranes. **Figure 10** represents the experimental thermal conductive variations of the polymer membranes. Nichrome thin wire is used as a heating element, and a T-type thermocouple wire is used for precise temperature measurements. The principle of this technique is based on Fourier's Law of Heat Conduction. For fluid samples, it can be given as (Assael et al., 2023),

$$\frac{dT}{dt} = - \frac{q}{2\pi\lambda r} \tag{3}$$

For the current applications, the above equation is modified, and it can be written as,

$$q = - k \frac{dT}{d(t)} \tag{4}$$

where, q is the rate of heat transfer through a material, and k is the thermal conductivity, $\frac{dT}{d(t)}$ is the change of temperature over time. A negative sign indicates that heat is flowing from a region with a higher temperature to one with a lower temperature. The rate of heat transfer through the material is given at 0.5 watts during the performance of this experiment. The thermal conductivity for the samples PCB0.5, PCB1, and PCB1.5 was found to be 0.1973 w/k, 0.14676 w/k, and 0.2493 w/k. Thus, it can be concluded that PCB1 carries less heat energy because its thermal conductivity is lower. Hence, PCB1 is better in the case of electroadhesive actuators to function in higher temperatures.

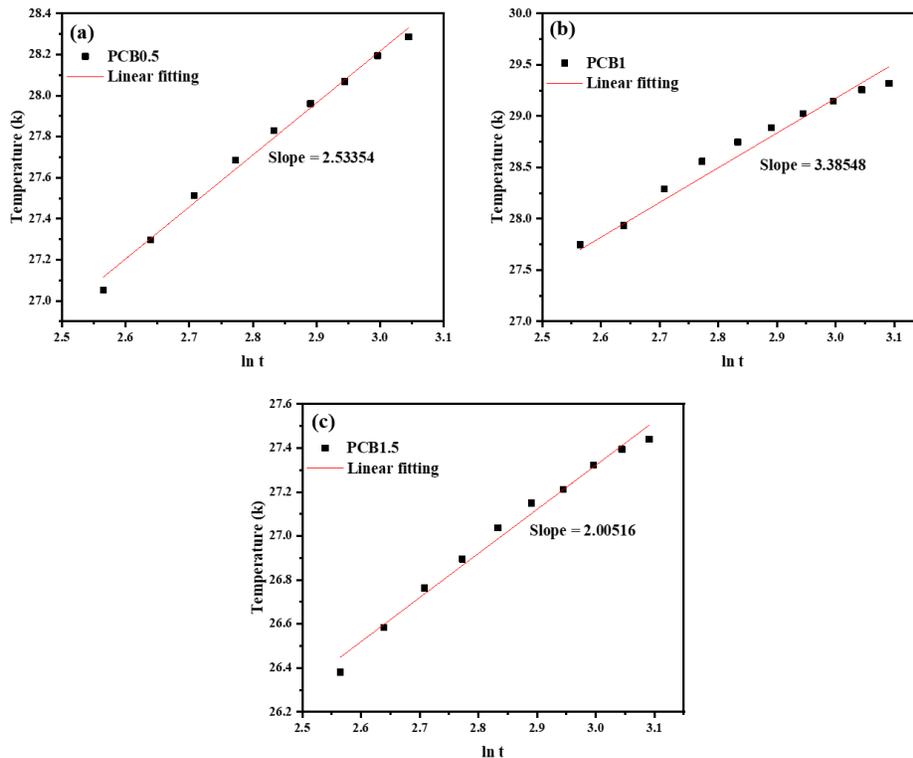


Figure 10. Experimental thermal conductive variations for (a) PCB0.5, (b) PCB1, and (c) PCB1.5 membranes.

4.6 Load-Bearing Test Analysis

A control unit is connected to the voltage power supply to control the voltages applied to the EA pads constantly. Electroadhesive forces are produced between the EA pads when a voltage is applied across the EA clutches. The source of power can be turned off to attain deadhesion (Guo et al., 2020). A positive voltage has been created on one pad and a negative voltage on the other pad. The gap between the two pads is affected by the electric field created by the voltage difference. The area between the dielectric tapes provides electric isolation and inhibits electric discharge. So long as the voltage is applied across the pads, an attraction force can be sustained (West et al., 2020; Feizi et al., 2022). The minimum activation voltage in the case of PCB0.5 far exceeds 150 V, making it less suited for EA clutches for lower power consumption. With a slight voltage rise in the instance of PCB1.5, the electroadhesive tape was damaged, leaving the spots behind. This might be a result of the CB's uneven dispersion over PVDF-HFP as observed from SEM analysis. As tabulated in **Table 1**, the clutch with PCB1 membrane activates at a lower voltage and holds the weight of about 550 g to 3550 g between 98 V to 550 V. It was found that PCB1 is more suited for electroadhesive actuator applications out of the three samples by providing a good conductive pathway for charge transfer and eliminating the issue of dielectric breakdown.

Table 1. Load-bearing analysis of various clutches.

Clutches	Load-bearing test using a DC-DC booster circuit							
	Minimum activation voltage (V)	Load-bearing (gm) at different voltages						References
		At Minimum activation voltage (V)	150 V	250 V	350 V	450 V	550 V	
PBN1	130	100 gm	100 gm	700 gm	850 gm	1050 gm	1500 gm	Ranjithkumar et al. (2023a)
PBNT1	138	350 gm	400 gm	950 gm	-	-	-	Ranjithkumar et al. (2023a)
PCB0.5	180	100 gm	-	-	-	-	-	Present work
PCB1	98	550 gm	2050 gm	2650 gm	3100 gm	3400 gm	3550 gm	Present work
PCB1.5	-	-	-	-	-	-	-	Present work

4.7 Contact Angle Measurement

The wetting properties of the surfaces are crucial in the analysis of the interaction, known as the contact angle (q), and the resultant value is related to the surface energy of the materials. It is widely acknowledged that a surface with an affinity for liquid contact angle smaller than 90 degrees is represented by a value of $q < 90$ degrees, and this surface is typically referred to as hydrophilic and the contact angle greater than 90 degrees is represented by a value of $q > 90$ degrees, and this surface is typically referred to as hydrophobic (Hebbar et al., 2017). The contact angle on polymers can provide important details about the wettability and adhesion characteristics of the material. Recognizing these contact angles is crucial for determining the ideal surface properties to operate electroadhesive clutches effectively. Polymers having a hydrophobic character may have several drawbacks when utilized as electronic conducting membranes. The hydrophobic nature can cause poor wettability, resulting in poor adhesive characteristics. Polymer films with a hydrophilic character provide various benefits that increase wettability, comfort, and adhesive qualities, making them better suited for electroadhesive clutches (Inoue et al., 2020).

The wettability measurements were typically conducted using water, as it is the most commonly utilized liquid. To simulate a more realistic scenario, a wettability test with sweat was also performed. This was done to better understand the adhesive behaviour of membranes for human-related electroadhesive clutch applications, as sweat contains salts and other organic components that may impact the membrane's interaction with moisture. From **Figure 11**, the fabricated PCB1 polymer membrane displays a hydrophilic character with $q < 90^\circ$ angle, indicating a hydrophilic nature for both water and sweat. This quality is advantageous for several reasons. Primarily, the hydrophilic character of the membrane amplifies its

electrical conductivity when it comes into contact with a dielectric membrane. Furthermore, the hydrophilic feature of the polymer membrane greatly improves its efficiency in adhesive applications. A hydrophilic polymer membrane may rapidly absorb moisture from its surroundings, allowing for more intimate interaction with adhesive materials. This leads to a stronger and more adhesive medium between the electronic conducting membrane and the dielectric layers.

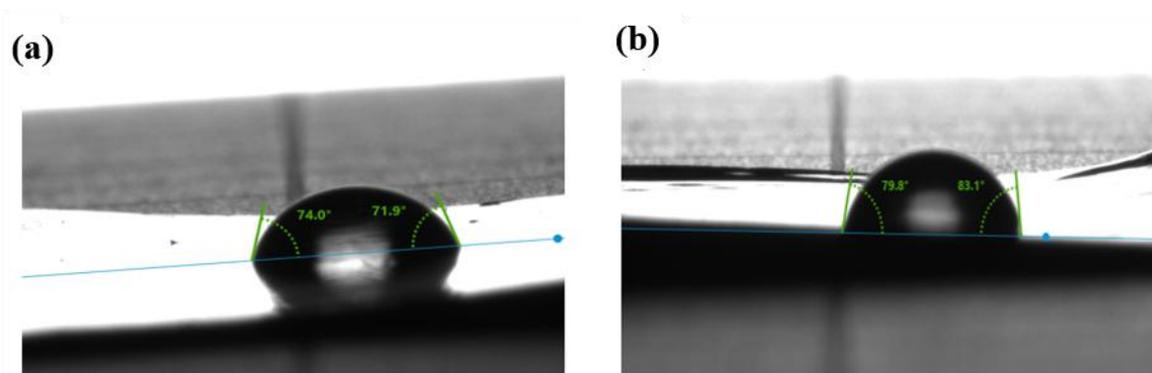


Figure 11. Wettability measurements for PCB1 membrane using (a) water and (b) sweat.

5. Conclusion

Employing CB/PVDF-HFP as an electrically conducting membrane, hBN/PVDF-HFP as a dielectric medium, and Cu-Ni conducting fabric tape as an electrode, flexible electroadhesive clutches with low power consumption were designed. Among the different compositions of electronically conducting membranes, the PCB1 fabricated membrane ensures a conductive pathway through which charge can be easily distributed, leading to an interaction between the electrodes with higher adhesion when the clutch is engaged. The conductivity of PCB0.5, PCB1, and PCB1.5 was found to be $0.0048 \text{ mS cm}^{-1}$, $0.0106 \text{ mS cm}^{-1}$, and $0.0438 \text{ mS cm}^{-1}$. From the load-bearing analysis, the experimental results confirm that PCB1 has load-bearing efficiency to withstand 550 g at a minimum voltage of 98 V. Thus, the presence of electronically conducting PCB1 membrane is an advantage to alleviate dielectric breakdown issues and also helps for quick responses. In conclusion, the developed electroadhesive clutch with its lightweight design and low power consumption is particularly advantageous for rehabilitation, robotic mechanisms, and geriatric healthcare.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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AI Disclosure

During the preparation of this work, the author(s) used generative AI in order to improve the language of the article. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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