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Dielectric elastomer with desirable thermal, mechanical, and dielectric characteristics for use as an actuator

C M VEERABHADRASWAMY
SELECTION GRADE LECTURER
Department of Mechanical Engineering,
Government Polytechnic Arakere(Srirangapatna)

ABSTRACT

Dielectric elastomers (DE) are an emerging class of electro-active materials capable of significant deformation in response to applied voltage. Differential scanning calorimetry (DSC), thermal gravimetric analysis (TGA), dynamic mechanical analysis (DMA), and a broadband dielectric spectroscopy (BDS) analyzer were used to investigate the thermal, mechanical, and dielectric properties of 3M's most popular dielectric acrylic elastomer (VHB 4910). The VHB 4910's glass transition temperature was measured using DSC to be about -40 degrees Celsius. The TGA analysis showed that VHB 4910 began to lose mass at about 250 degrees Celsius. DMA measurements revealed a frequency- and temperature-dependent rise in the storage modulus of VHB 4910. VHB 4910's dielectric constant rose with temperature up to 0 degrees Celsius, then decreased to 100 degrees Celsius. Dielectric elastomer actuators (DEA) made from VHB 4910 were studied for their mechanical and electrical efficacy. It was shown that the mechanical properties of the elastomer dominate the actuation performance, while the frequency and temperature dependence of the dielectric properties have less of an effect; this may be used to guide the design of actuator configurations and the choice of actuator materials.

Keywords: actuation, dielectric elastomer, dielectric properties, efficiency, mechanical properties, thermal properties

I. INTRODUCTION

Micro pumps, robotics, and artificial muscles are just some of the high-performance applications that make use of dielectric elastomers. VHB 4910 (3M, USA) is an acrylic copolymer that has excellent electromechanical conversion efficiency (6090%), a significant actuation strain of up to 380% in area, stress up to 7.2 MPa, and a very high elastic energy density (3.4 J/g). In Fig. 1 we see the molecular structure of VHB 4910.[1] VHB 4910 films have shown such exceptional performance because of the significant uniaxial or biaxial pretrain that increases the polymer's dielectric breakdown strength for a given thickness.[2–4] Dielectric elastomer actuators (DEA) based on the developments of VHB 4910 films have shown their popularity in applications, despite the availability of many other types of actuators based on different mechanisms of actuation, such as chemically activated, shape memory type, and light, magnetically, and thermally activated types. As can be seen in Fig. 1, the films are often utilized as a stretchy capacitor and sandwiched between two pliable electrodes.

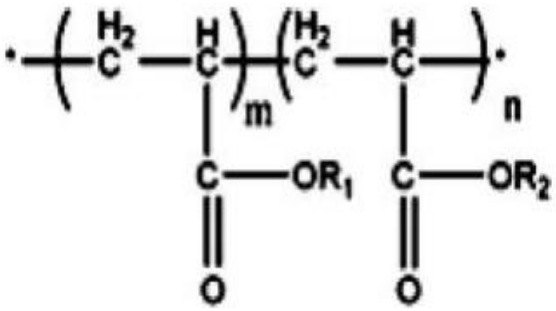

Figure No. 1*: Commercial trade secrets related to the chemical composition of VHB 4910 acrylic elastomer with m, n, and R2.*

When an electric current is sent through an elastomer, the material things out and increases in size dramatically. While parallel stretching keeps charges apart, compression pulls opposing charges closer together. These transformations are the engine that transforms electrical energy into mechanical work. The following equation establishes an

electrostatic relationship between actuator parameters and material parameters.

$$P = \varepsilon_0 \varepsilon_r E^2 = \varepsilon_0 \varepsilon_r (\frac{v}{z})^2$$

where E is the electric field, V is the applied voltage, z is the thickness of the film, P is the effective pressure, r is the dielectric constant, 0 = 8.85 1012 F/m is the permittivity of vacuum. The thickness strain Sz is proportional to the actuation pressure divided by the modulus of elasticity Y, for small strains:

$$S_z = -\frac{-p}{y} = -\varepsilon_0 \varepsilon_r \frac{E^2}{y}$$

These equations aid in the definition of certain generic material requirements, such as the necessity for a high dielectric constant, a strong breakdown field, and a low elastic modulus to withstand a high effective pressure and a significant strain. High efficiency and quick reaction time need a material with minimal electrical and mechanical losses.

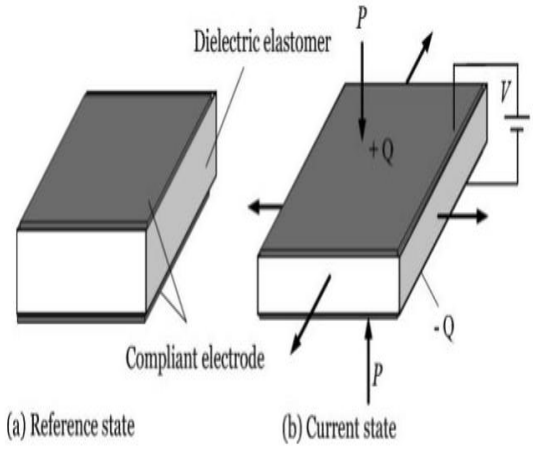

Figure No. 2*: Actuation of the dielectric elastomer*

There has been a lot of work done in the past to simulate the performance of DEAs based on VHB 4910 elastomers, and the mechanical behavior of this material has been studied extensively. Multiple researchers have examined the electrically relevant variations in the dielectric constant of VHB 4910 over broad frequency and temperature ranges.[13] Below 100 Hz, VHB 4910 films were tested to have a value of 4.7 0.14 at room temperature.[12] Although temperature was not a factor, **Palakodeti and Kessler**[14]'s dynamic mechanical measurements of pretrained VHB 4910 films in the frequency range 5-20 Hz suggested an improvement in efficiency at lower frequencies, implying better DEA performance in these circumstances. Despite establishing a quantitative description of the frequency-dependent dielectric and mechanical behavior of VHB 4910 elastomers for actuator applications, **Molberg et al.** [15] failed to describe the thermal behavior and temperature-dependent dielectric and mechanical behavior of their samples, demonstrating instead that the frequency dependence of the elastic response predominated the actuator performance.

In this study, we report on experiments that establish a connection between VHB 4910's thermal and electromechanical characteristics. Several material characteristics were characterized that are crucial for the development and deployment of devices based on VHB 4910. DSC and TGA were first used to characterize the thermal characteristics, such as thermal stability, of the VHB 4910 films. In addition, the effect of frequency and temperature on the mechanical efficiency of the actuators was characterized by analyzing dynamic mechanical parameters such as the elastic and loss moduli using dynamic mechanical analysis (DMA). Finally, broadband dielectric spectroscopy (BDS) was used to study the films' dielectric characteristics. Mechanical and electrical actuation performance under the effect of these features were evaluated.

II. EXPERIMENTAL

2.1: Materials

The 3M Company (St. Paul, MN, USA) provided the poly-acrylic dielectric polymer employed in our study. In this research, we chose to study dielectric elastomer samples of VHB 4910 with dimensions of 30 mm in width and 1 mm in thickness. Transparent tape made from this polymer that has adhesive on both sides and can withstand significant deformations is commercially available. Three replicates of each measurement were tested.

2.2: Characterization

Differential Scanning Calorimetry (DSC) Using DSC, we can accurately determine the VHB 4910 samples' Tg (glass transition temperature). The materials were subjected to DSC examination in a flowing nitrogen environment using a DSC 822e (Mettler Toledo, Switzerland) calorimeter. The samples, whose weights ranged from 20.0 mg to 21.0 mg, were heated to 100°C at a rate of 20°C/min,

kept there for 5 minutes to remove any remaining thermal history, and then cooled to 25°C at the same rate.

Analysis by use of thermal gravimetry. With a TGA/SDTA 851 analyzer (Mettler Toledo, Switzerland) and a nitrogen atmosphere purge rate of 40 mL/min, the thermal stability of the VHB 4910 films was tracked from 25 to 500 degrees Celsius at a heating rate of 10 degrees Celsius per minute. Mechanical Analysis of Dynamic Systems. Experiments using dynamic mechanical analysis (DMA) were performed in tension mode at a frequency range of 0.1-70 Hz utilizing a TA DMA Q800 (TA Instruments, Chicago, IL, USA) equipment. The samples were heated at a rate of 2 degrees Celsius per minute and evaluated between -80 and 80 degrees Celsius.

III. METHODOLOGY

3.1: Thermal Properties

VHB 4910 requires consideration of environmental factors including temperature and humidity in actuator design and operation. DSC is a great tool for describing the properties of glass transition. Figure 3 displays the thermogram produced by the DSC. VHB 4910 has a glass transition temperature of -40 degrees Celsius. These specimens Tg measurements are consistent with the previously reported value (39 degrees Celsius).

TGA was used to study the VHB 4910 film's resistance to heat. As can be seen in Figure 4, VHB 4910 begins to lose density at about 260C. At roughly 385 degrees Celsius, rapid weight loss begins.

3.2: Mechanical Behavior

The dynamic moduli of storage and loss, as well as the tan behavior as a function of temperature and frequency, were measured using DMA. The moduli of storage and loss for VHB 4910 at 0.1 Hz are shown in Figure 5 as a function of temperature. Typically, the storage modulus and loss modulus of an amorphous polymer would shift by three to four orders of magnitude during the glass transition.

In the same temperature range, the elastic modulus of VHB 4910 was 1200 MPa at -40°C and decreased to about 0.1 MPa at 100°C, while the loss modulus decreased from 200 MPa to around 0.03 MPa. In addition, the storage modulus could not be precisely measured when the temperature of the material was over 100 C, since it became too soft, like an elastic fluid. The results show that the elasticity of VHB 4910 is highly temperature dependent. The material stiffens up considerably and the strain response diminishes at low temperatures.

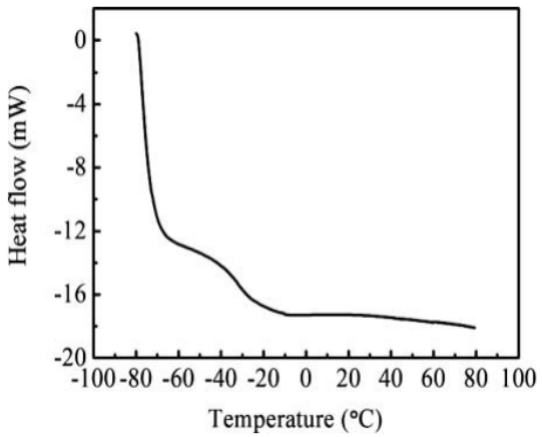

Figure No. 3*: DSC thermogram of the VHB 4910*

The dynamic mechanical tests yielded a temperature-frequency (0.1 Hz) plot of the mechanical loss factor (tan) and storage modulus (Figure 4). VHB 4910 has a wide glass transition, from below fifty degrees Celsius to over sixty degrees Celsius. For the VHB 4910 film, tan was lower at lower temperatures (40 C) and higher at higher temperatures (10 C). From 10 degrees Celsius to 100 degrees Celsius, the tan progressively reduced.

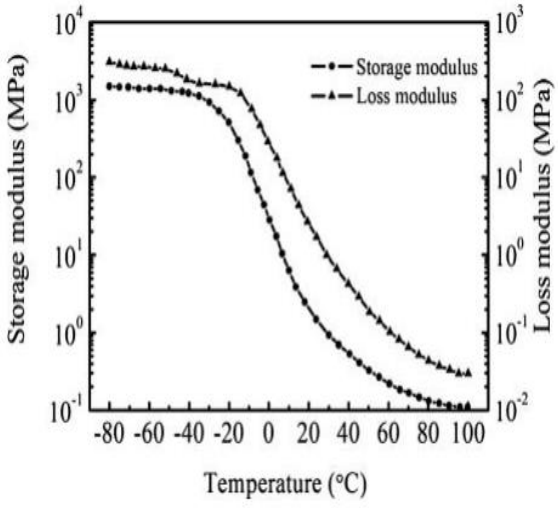

Figure No. 4*: Storage and loss moduli as a function of temperature at a frequency of 0.1 Hz.*

The mechanical loss factor, tan, and the storage modulus, ob, are shown in a plot in Figure 4 shows the frequency dependence of the loss factor, storage modulus, and loss modulus from 0.1 to 70 Hz at 35 degrees Celsius. Storage and loss moduli both rose from 0.2 MPa to 1.5 MPa when the frequency was raised (see Figure 4). tan, the mechanical loss factor, peaked at 1.23 at 45 Hz and dropped to 1 at 70 Hz (see Fig. 7). The tan describes the mechanical damping or internal friction of a viscoelastic system and is stated in terms of the recovered energy lost each cycle.

The mechanical and electrical losses inside the elastomer are what define how efficient an actuator is.[14] The viscoelastic property, tan, of the materials influences the overall efficiency of an actuator, which is proportional to the mechanical efficiency.

$$\wp_m = \frac{1}{1 + \pi tan_\delta}$$

Figure 5 shows how frequency and temperature affect VHB 4910's mechanical efficiency. Maximum frequency-dependent efficiency was found to be 28% at 5 Hz, while maximum temperature-dependent efficiency was found to be 68% at -40°C.

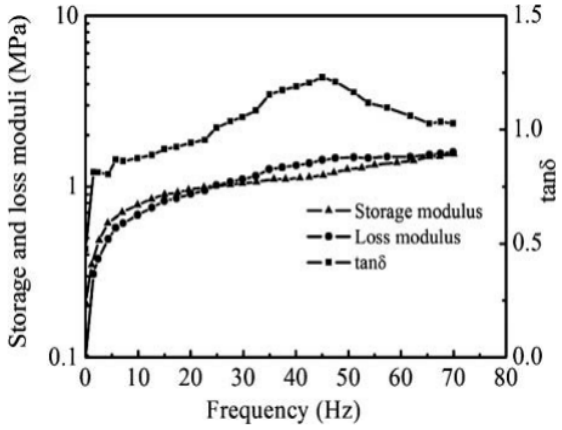

Figure No. 5*: Frequency dependence of loss factor, storage, and loss moduli at 35◦C.*

dependence. The VHB 4910's mechanical efficiency dropped dramatically from 5 to 45 Hz, suggesting a rise in wasted effort. Above 10 degrees Celsius, VHB 4910 films' mechanical efficiency rose steadily.

3.3: Dielectric Constant and Loss Factor

Figure 5 depicts the frequency-dependent variations in the dielectric constant and loss factor from -100 degrees Celsius to 100 degrees Celsius. As frequency increased, the dielectric constant dropped dramatically. This is because the dipoles' inability to keep up with the growing AC frequency reduced the orientational polarization, and therefore the dielectric constant, making high-frequency materials less effective.

Figure 5 shows the dielectric constant as a function of temperature from absolute zero degrees Celsius up to a high temperature. This is because dipoles cannot orient spontaneously at low temperatures, and orientation polarization is connected to the thermal motion of the molecules. Since it is simpler to orient the dipoles as the temperature rises, the orientation polarization increases, and the dielectric constant rises as a result. The dielectric constant dropped from 0 C to 100 C when the temperature was raised from cold. The amplitude of the molecules' random thermal motion increased as the temperature increased from zero to one hundred degrees Celsius. This indicates that the dielectric constant fell since the range of variation from perfect alignment with the electric field was higher, and so the molecules were less tightly aligned with one other.

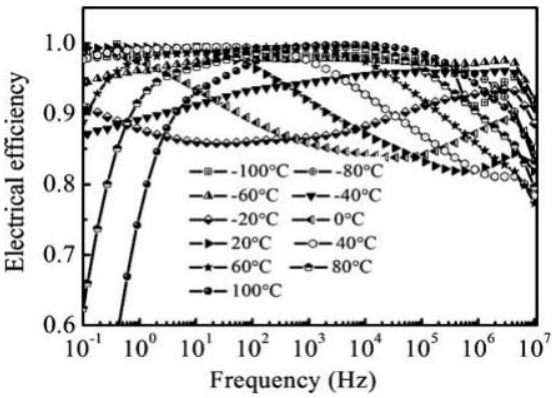

Figure No. 6*: Electrical efficiency of the VHB 4910 at different temperatures.*

However, a relaxation peak can be seen over many orders of magnitude in frequency in Fig. 5's loss graph, which is most pronounced in the frequency range of 20C to 20C. This peak, which is triggered by heat, is characteristic of the well-known -relaxation process in polymers [12], which is linked to the motion of chain segments. It has been

suggested that the actuator's ability to transfer electrical energy into mechanical work at a high efficiency is crucial. Dielectric losses, tan, are proportional to the electrical efficiency, e, of the VHB 4910 film/gold structure.

$$\wp_m = \frac{1}{1 + \pi tan_\delta}$$

The relationship between frequency and electrical efficiency at different temperatures is shown in Figure 6. For the most part, the electrical efficiency is rather good. This polymer's highest efficiency was about 0.98 at room temperature (20 C) and low frequencies (10 Hz), which is a satisfactory number and represents little electrical losses. Figure 6 shows that when electrical and mechanical efficiencies are compared, the former is noticeably greater while the latter is dominated by mechanical losses.

IV. RESULT

Circular specimens were biaxially positioned for electromechanical testing. As can be seen in Fig. 6, the VHB 4910 film was mounted to a sturdy frame and stretched in both directions. In the middle of the specimen, a circular region (8 mm in diameter on the inside) was painted with conductive carbon grease paint (MG Chemicals, Toronto, Ontario, Canada) and wired to a high voltage source. In this study, we selected three distinct equal biaxial pretrain ratios (100, 200, and 300%) and pushed the voltage up until we reached failure.

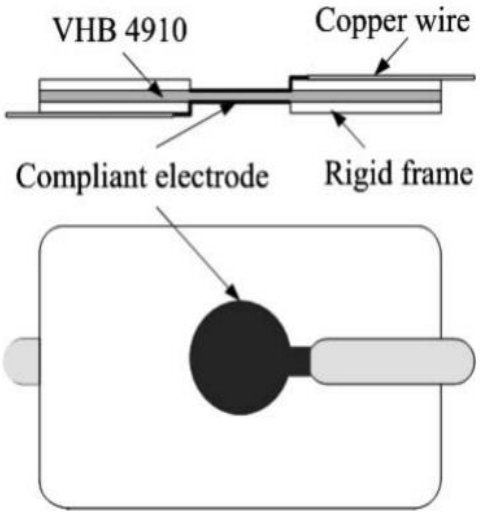

Figure No. 7*: Configuration of the specimen used for electromechanical experiments.*

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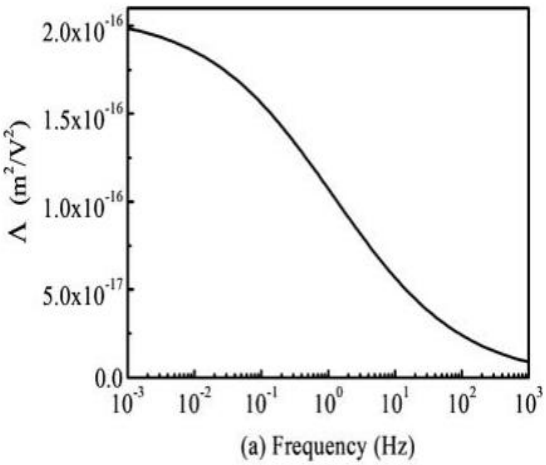

Figure No. 8: *Actuation factor as a function of frequency at 35◦C.*

By deriving a frequency-temperature dependency of the actuation factor = 0r Y, we can directly qualify the actuator performance of the materials. The modulus of storage Y is the result of the evaluation. The actuation factor provides a quantitative description of the electromechanical characteristics of a DE.

In Figure 7, we see the relationship between frequency and temperature at 35 degrees Celsius and 0.1 hertz. As the frequency rose, the actuation factor dropped, whereas the opposite was true for the temperature. VHB 4910's mechanical qualities largely determined its actuation performance since its dielectric properties hardly changed during the frequency and temperature range studied. In addition, the actuation varied by almost four orders of magnitude from 40°C to 80°C, and it was especially low at high frequencies.

V. CONCLUSION

DSC, TGA, DMA, and dielectric spectroscopy were used to create a quantitative description of the thermal and electromechanical behavior of VHB 4910. According to DSC testing, the glass transition temperature of VHB 4910 was somewhere about 40 degrees Celsius. The acrylic elastomer VHB 4910 has an elastic modulus that was very temperature and frequency sensitive. As a function of frequency, the dielectric constant rose until it hit a plateau at a certain temperature. Significant, and very temperature- and frequency-dependent, efficiency. The effect of frequency and temperature dependence of the dielectric properties on the behavior of the actuators was relatively small, but the electrical efficiency was much higher than the mechanical efficiency, and the mechanical response of the elastomer dominated the actuation performance.

This finding is relevant for materials development and selection in DEA applications because it demonstrates that actuator performance and actuation efficiency can be predicted from independently determined material parameters using the definitions in Equations (3), without the need for a strain energy function or calculations based on complex geometries.

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