Evaluation of Selected Dielectric Elastomers for use in an Artificial Muscle Actuator

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Abstract

This paper presents the results of a series of experiments designed to measure the suitability of selected dielectric elastomers as artificial muscle actuators. The paper aims to differentiate between three widely used dielectric elastomers, 3M VHB-4910, BJB Enterprises TC-5005 and NuSil Technology's CF19-2186. The materials are compared in terms of their ease of manufacture, strain, electrical properties and hysteresis. The effect and the importance of prestraining each material is also considered. A conclusion is drawn on the basis of these comparisons and recommendations are given for the design of actuators utilising these materials.

1 Introduction

The development of a realistic artificial muscle has potential applications in many fields of engineering. Natural muscle, as a product of billions of years of evolution, is a highly sophisticated and efficient actuator. In addition to producing large linear strains and having a high power to weight ratio, natural muscle displays flexibility, speed and passive force blocking capability. Consequently the creation of an actuator that is able to imitate natural muscle is highly desirable for fields such as medicine, robotics and defence.

An important subclass of the many different technologies that have been proposed as potential artificial muscles is the field of electroactive polymers (EAPs). EAPs tend to be lightweight, fast and capable of achieving large amounts of strain [Pelrine *et al.*, 2002]. They are able to produce direct linear motion, unlike traditional electric actuators which produce rotary motion. In addition, their electrical properties make them much easier to control than pneumatic or hydraulic actuators.

A particularly promising type of electroactive polymer is the dielectric elastomer. Dielectric elastomers are constructed by coating either side of a thin polymer film with a compliant electrode [O'Halloran and O'Malley, 2004]. A large potential difference is applied across the electrodes, and this induces a compressive stress in the polymer, according to Equation 1.

$$p = \varepsilon\varepsilon_0 E^2 \tag{1}$$

where p is the compressive stress, ε is the relative dielectric constant of the polymer, ε_0 is the permittivity of free space and E is the applied electric field (applied voltage divided by the distance between the electrodes). Thus the thickness strain of the dielectric elastomer can be calculated using Equation 2.

$$s = -\varepsilon\varepsilon_0 \frac{E^2}{Y} \tag{2}$$

where s is the thickness strain, Y is the Young's modulus and the other terms are as above.

Current research into dielectric elastomers has focussed on silicone and acrylic polymers [Pelrine *et al.*, 2000]. The aim of early work was to identify materials that combined relatively high dielectric constants with low elastic modulus and high dielectric breakdown strength. Once such polymers were identified, tests were carried out to determine the amount of strain that they could produce. A significant discovery from this early work was that prestraining the polymer before applying the electric field significantly improved performance [Pelrine *et al.*, 2000]. However, to date little has been published to show exactly how the properties of a dielectric elastomer change with the amount of prestrain.

The requirement that dielectric elastomers be prestrained in order to achieve the best performance produces difficulties in building an actuator based on this technology. Since dielectric elastomers need to be thin (from 1 mm down to less than 200 μm thick [Pelrine *et al.*, 2000]) and are lightweight (around the density of water [Bar-Cohen *et al.*, 1998]), any frame or structure for prestraining would usually contribute the majority of the size and weight of an actuator. This obviously reduces the power to weight ratio of the actuator and restricts the flexibility of any actuator design. Thus the design of an artificial muscle actuator based on dielectric elastomers must balance the need for high output strains (and hence high prestrains) with the desire for high power density and flexibility.

One method that has been proposed to reduce the dependence on prestrain is to load the polymer with high dielectric constant ceramic powder [Carpi and De Rossi, 2005]. Ceramics, such as titanium dioxide, can have dielectric constants that are orders of magnitude higher than those of dielectric elastomers. Thus, mixing a ceramic powder into a dielectric elastomer should produce a polymer with a much higher dielectric constant, offset by an increased modulus of elasticity [Carpi and De Rossi, 2005].

In this study, two silicones, BJB Enterprise's TC-5005 and NuSil Technology's CF19-2186, and one acrylic, 3M's VHB-4910, were chosen for further investigation. The VHB-4910 acrylic has been widely reported as being capable of producing very large output strains (over 100%), and has been used to produce linear expanding actuators [Zhang *et al.*, 2006]. However, the reported tests of this polymer indicate that high amounts of prestrain (up to 500% in one direction, or 300% in both lateral directions) must be applied before such outputs are produced [Pelrine *et al.*, 2000]. The two silicones, on the other hand, have been reported to produce much lower strains (5 to 60%), but do not appear to require as much prestraining [Carpi *et al.*, 2005; Pelrine *et al.*, 2000].

It has been noted that the VHB-4910 acrylic exhibits higher viscoelastic properties and higher leakage currents than silicone polymers [Plante and Dubowsky, 2007]. However, these effects do not seem to have been quantified. Viscoelastic behaviour in a polymer will contribute to hysteresis and creep in an actuator, and will also limit the allowable frequencies of operation. Ideally, a dielectric elastomer will behave like a capacitor, and so will only consume power when the input voltage is changing. However, leakage current will cause the elastomer to consume power at DC voltages as well, possibly leading to significantly higher power usage.

In this work, tests were undertaken on the three elastomers mentioned above to provide a greater characterisation of the effects of prestraining and the electric properties of the polymers. The overall goal of these tests was to provide sufficient data to aid in the selection of an appropriate dielectric elastomer and the subsequent design of an artificial muscle actuator.

Natural muscles can produce strains of up to 40%, although they are rarely required to reach this limit [Lieber, 1999]. Rather, the majority of muscles are only required to produce strains of up to 19% [Burkholder and Lieber, 2001]. Thus an artificial muscle actuator should be able to produce strains of between 20% and 40%. Further to this, the artificial muscle should consume a minimal amount of power when actuated and should not display a significant amount of hysteresis.

2 Materials and Manufacture

The three materials (VHB-4910, TC-5005 and CF19-2186) were chosen based on current literature and availability. The 3M VHB-4910 was purchased as a pre-manufactured tape that was 24mm wide and 1mm thick. NuSil Technology's CF19-2186 came in two separate components that needed to be mixed together and cured. BJB Enterprise's TC-5005 came in the form of three separate components, A, B and C. Component C was a softener which could be added in varying amounts to a fixed mixture of components A and B. For these tests, the TC-5005 was manufactured without using softener.

Titanium dioxide powder was also obtained to test the proposal by Carpi and De Rossi [2005] that it could improve the dielectric properties of the silicones. The performance of each of the materials was also expected to improve significantly as the thickness of the material decreased. This can be seen from Equation 1, which states that the actuation pressure is proportional to the square of the applied electric field. Thus a reduction in thickness should create a large improvement in strain at a fixed voltage, or alternatively reduce the voltage required to produce a certain amount of strain. Consequently the goal of the moulding process was to produce material of at most one millimetre in thickness. The quality and the consistency of the material were also of importance. When impurities were present in the materials, the tests resulted in premature irreversible failure of the polymer.

2.1 Moulding

A vacuum moulding process was used to mould the two silicones. This was necessary to ensure the removal of air bubbles formed during mixing. Following this, the material was clamped between two Perspex plates to cure. A spacer was placed in between the two plates to determine the thickness of the film. The size of the available vacuum chamber limited the final dimensions of the films to 100mm by 120mm.

2.2 Moulding Results

This process successfully produced impurity-free TC-5005 films to thicknesses of 0.25 millimetres. The same process was unsuccessful when applied to NuSil Technology's CF19-2186. Due to the material's highly viscous nature it was difficult to remove all the air bubbles from the films, and in addition the desired thicknesses could not be achieved. Although it was eventually possible to produce consistent CF19-2186 films, the thickness restriction meant that it was not possible to produce large enough electric fields to actuate the material with the current equipment. Thus no formal tests were completed using the CF19-2186.

TC-5005 mixed with 10% titanium dioxide was successfully moulded at thicknesses down to 0.25mm. However the texture of the material was not consistent. Great difficultly was had in consistently producing impurity free TC-5005 with 10% titanium dioxide. The titanium dioxide powder tended to clump together rather than mix uniformly throughout the polymer. Surface flaws were also magnified, resulting in tears in the films when they were stretched. The addition of titanium dioxide should have increased the dielectric constant of the polymer, while also increasing the elastic modulus. However, the successfully moulded materials exhibited far lower performance than TC-5005 without any titanium dioxide. In fact, the tests undertaken with this material showed negligible area strain. Thus the tests of TC-5005 with titanium dioxide were not continued.

3 Experimental Method

The chosen materials were prestrained onto a rectangular frame and compliant electrodes were applied evenly to both sides. A power supply driven by a pulse width modulated (PWM) signal was then used to produce a stepped sequence (10 seconds on and 10 seconds off) of increasing voltage levels to actuate the dielectric elastomers.

Videos of the tests were recorded using a digital camera, and subsequently analysed using image processing techniques in MATLAB.

3.1 Material Preparation

The dielectric elastomer sheets were prestrained onto a rigid frame that could be adjusted to provide different levels of prestrain. In addition to changing the dielectric properties of the material, the prestraining ensured that strain was expressed in the plane of the sheet and buckling effects were minimised. The configuration is shown in Figure 1.

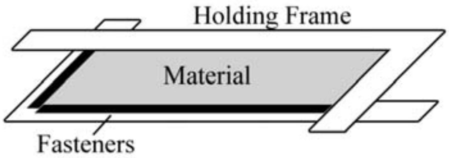

Figure 1: Prestrain setup showing adjustable frame for variable prestrain.

Each test was carried out with an equal amount of applied prestrain in both lateral dimensions. The VHB-4910 was tested with 10%, 50%, 100%, 150% and 200% prestrain applied in each direction, while the TC-5005 was tested with 10%, 25% and 50% prestrain in each direction. The TC-5005 had a higher elastic modulus than the VHB-4910, and so it was not feasible to uniformly stretch it to larger prestrains.

Conductive carbon grease was used as a compliant electrode and applied to both sides of the material. The electrode area was kept significantly smaller than the surface area of the polymer to prevent arcing and to maintain tension on the active region. A stencil was used to ensure the electrode was applied uniformly across the material.

Connection of the electrode to the power supply was achieved by attaching electrical contacts to either side of the material using silicone glue, and painting carbon grease trails to connect the contacts with the electrode areas. A completed test setup is shown in Figure 2.

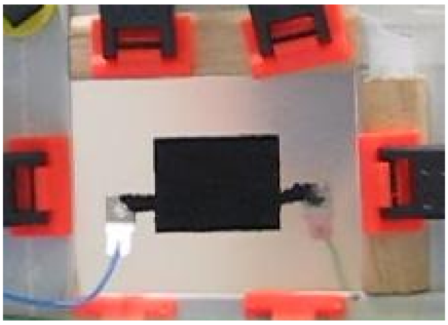

Figure 2: Test piece of TC-5005, prestrained with electrodes applied.

To supply the necessary electric field to actuate the elastomers, a power supply was built that was rated at a maximum voltage and current output of 30kV and 120uA, respectively. The supply voltage output could be driven by PWM signals from a microcontroller. A high voltage probe was built so that the voltage output from the supply could be measured and recorded during testing. In addition, a 100kΩ resistor was connected in series with the dielectric elastomer. Measuring the voltage drop across this resistor provided an estimate of the current flow through the polymer.

4 Results and Discussions

Both materials tested were shown to be able to achieve the desired minimum amounts of strain as per the selection criteria previously mentioned. This means that they both have the potential to be used in an artificial muscle actuator, although the actual strain produced by the actuator will depend heavily on the design. A pictorial comparison of the actuated and unactuated states for 3M VHB-4910 is shown in Figure 3.

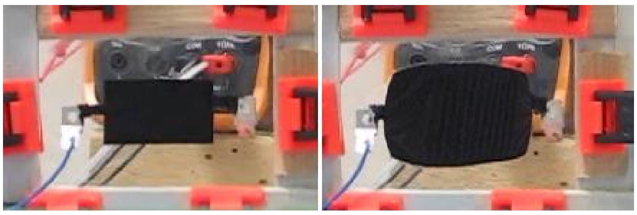

Figure 3: VHB 4910 with 200,200% prestrain in initial and actuated states.

In terms of electrical properties, the VHB-4910 was shown to consume less power than the TC-5005 prior to breakdown; however the VHB-4910 was discovered to have much lower dielectric breakdown strength than the TC-5005.

Analysis of the hysteresis and creep of both materials indicated that the VHB-4910 displays significant creep, likely due to it’s highly viscoelastic nature. The TC-5005 on the other hand showed more favourable characteristics with no significant creep effects.

4.1 Achievable Strain

The strain achievable for a given voltage or electric field strength is of importance when considering the design of an actuator. The amount the material was prestrained as well as the thickness of the material will affect the strain response of the material. The strain of the material is measured in terms of area strain. Area strain, δ, is defined in Equation 3, as

$$\delta = \frac{\textit{Current electrode area}}{\textit{Initial electrode area}} - 1 \qquad (3)$$

The relationship between area strain and applied voltage for 3M VHB-4910 can be seen in Figure 4. Measurement data is shown as series of points, and curves of best fit have been plotted through them.

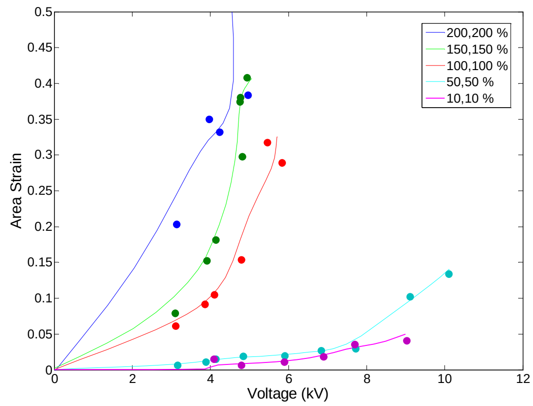

Figure 4: 3M VHB-4910: Area strain as a function of voltage.

The breakdown of the material is also visible in Figure 4. Breakdown can be identified by a continuing increase in strain at relatively constant voltage. The material can be seen to break down at 4 kV in the 200,200% prestrain case, and at slightly higher voltages in the 150,150% and 100,100% prestrain cases.

The prestrain of each curve seems to greatly influence the resultant strain. Higher values of prestrain resulted in larger amounts of area strain at lower voltages. The largest prestrain, two hundred percent, generates almost one hundred percent strain at 4 kV. This constrasts to the ten precent prestrain case which generated under one percent area strain at the same voltage.

This trend is also seen for BJB Enterprise's TC-5005, as shown in Figure 5. The 25,25%, half-millimetre thickness test produced less strain than the 50,50% prestrain case, as would be expected. However the 25,25%, quarter-millimetre thickness test exceeded the other tests in terms of area strain per unit voltage. This is consistent with the theoretical understanding of the relationship between material thickness and electric field strength and electric field strength and area strain. It is clear from this that the thickness of the material used in the actuator design must be considered as well as the amount of prestrain used.

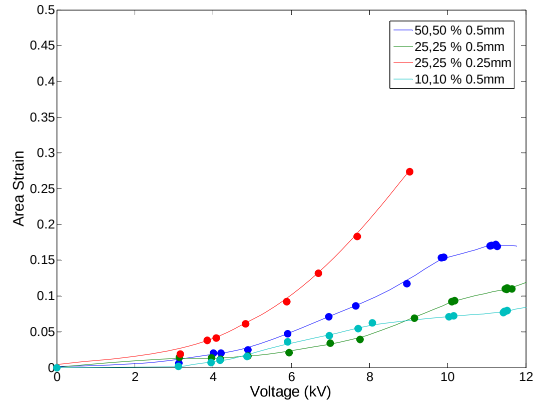

Figure 5: BJB Enterprise's TC-5005: Area strain as a function of voltage.

The electric field strength across the material is defined in Equation 4.

$$E = \frac{V}{t'} \qquad (4)$$

where V is the voltage applied across the material and t' is the current thickness of the material. The thickness of the material is dependent on the prestrain as well as the current area strain of the material. Therefore, assuming that the material volume remains constant, for a given prestrain α in both directions and current area strain δ the current thickness of the material t' is given by Equation 5, where t is the original thickness of the material.

$$t' = \frac{t}{(1+\delta)(1+\alpha)^2} \qquad (5)$$

Using Equations 4 and 5 the electric field strength can be calculated based on the voltage applied to the material, the prestrain of the material and the current area strain, as can be seen in Equation 6.

$$E = \frac{V(1+\delta)(1+\alpha)^2}{t} \qquad (6)$$

The relationship between area strain and electric field strength for BJB Enterprises TC-5005 can be seen in Figure 6.

This shows that the effect of prestrain can be explained to a large extent by taking into account the change in thickness of the material. Hence for a given electric field strength it is possible to predict the area strain of the TC-5005 material, independent of the prestrain or the thickness of the material. This result is not as clear for 3M's VHB-4910 as can be seen in Figure 7. However if the areas of material breakdown are excluded then a similar dependence can be seen. The breakdown regions can be identified by a rapidly increasing slope or by referring to Figure 11.

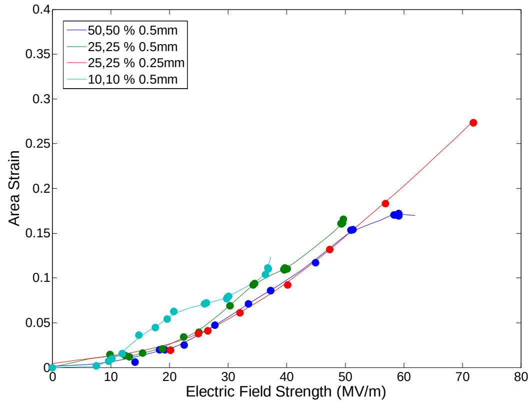

Figure 6: BJB Enterprises TC-5005: Area strain as a function of electric field strength.

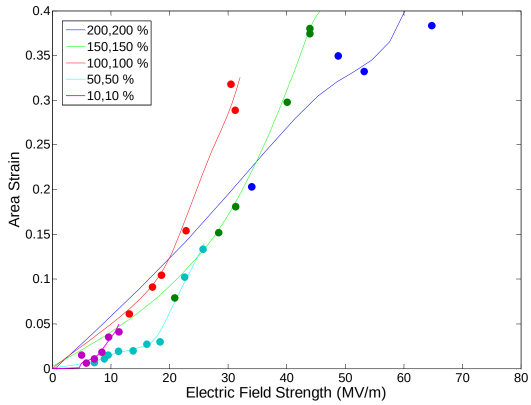

Figure 7: 3M VHB-4910: Area strain as a function of electric field.

As can be seen, a comparison between the two materials based on electric field strength and area strain is more sensible than a comparison based on voltage and area strain. Figure 8 shows approximate lines of best fit for both materials. As can be clearly seen the VHB-4910 has a significantly higher response than the TC-5005. This indicates that for a given electric field strength the VHB-4910 will produce greater area strain than the TC-5005. Solely on the basis of strain, the VHB-4910 is superior to the TC-5005 material.

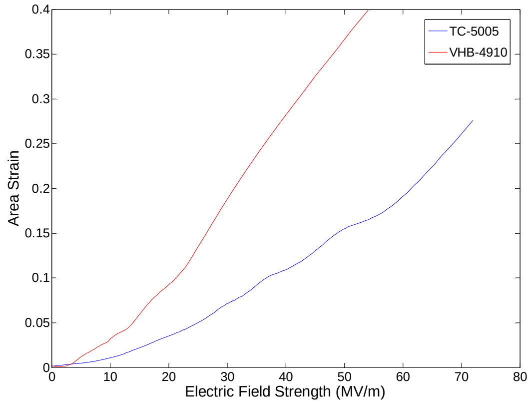

Figure 8: Strain-electric field strength trends for VHB-4910 and TC-5005

4.2 Electrical Properties

Theoretically, dielectric elastomer materials are insulators, and so the dielectric elastomer should electrically behave as a capacitor. However, due to the high voltage used, leakage current can become significant. Thus leakage current must be taken into account when determining power consumption.

The dielectric elastomers can be simplistically modelled as a capacitance and resistance in parallel. The capacitive behaviour of the material is noticeable when the applied voltage is changing. This corresponds to the ideal behaviour of the material. However, the resolution of the test data available was not sufficient to model the capacitance accurately; hence it is not presented in this paper. The resistive behaviour of the material (i.e. leakage current) is measurable when DC voltages are applied. This appears to be the dominant factor contributing to power consumption.

Another important electrical property of the materials is their dielectric breakdown strength, which is the applied electric field at which the material starts to conduct increasing amounts of current without increases to the applied electric field.

Due to its low dielectric breakdown strength, the 3M VHB-4910 is unsuitable in its unstrained state for use in the construction of an artificial muscle actuator. However, prestraining the material can significantly improve the breakdown strength [Pelrine *et al*., 2000].

To compensate for the effects of electrode area and material thickness on total resistance, the resistivity of each material was calculated from the test data. A plot of the resistivity of the VHB-4910 is presented in Figure 9. The data for the 10,10% and 50,50% prestrain tests were omitted due to incomplete data ranges, as these tests were unable to produce enough actuation strain to drive the electric field to the breakdown region.

From the plot it can be seen that the resistivity of the VHB-4910 at 100,100%, 150,150% and 200,200% increases linearly until a sudden drop occurs at electric field strengths of 20, 33 and 56 MV/m respectively. During the linearly increasing range, the overall resistance of the material, if plotted, is fairly constant. The sharp drops in resistivity correspond to the dielectric breakdown of the material. However repeated tests showed that when the applied electric field was removed after breakdown, the VHB-4910 material was able to recover its original resistivity. This plot also confirms that the dielectric breakdown strength increases as the amount of prestrain is increased.

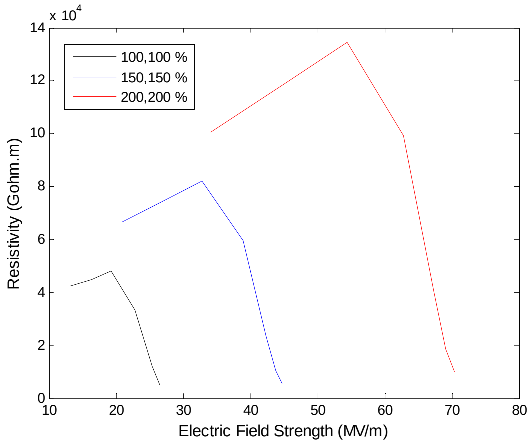

Figure 9: Resistivity plot of VHB-4910 at varying prestrain values

Figure 10 shows a plot of the resistivity for different prestrains of the BJB Enterprises TC-5005. None of the tests were able to determine the dielectric breakdown strength of TC-5005, however it can be seen from the plots that relative to the resistivity of VHB-4910, the resistivity of the TC-5005 is much more stable across the range of electric field strengths applied. When this is converted to overall resistance, it indicates that the resistance of this material will decrease with increases in electric field. Thus it seems that the observed resistance changes in TC-5005 were primarily due to geometrical changes in the material. It is clear that the material's dielectric breakdown strength is much higher than the electric field strengths that were applied in these experiments.

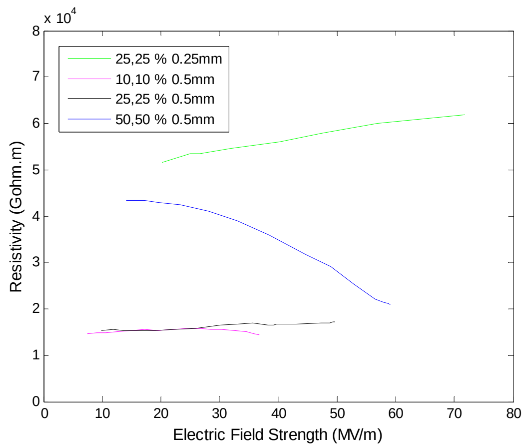

Figure 10: Resistivity plot of TC-5005 at varying thickness and prestrain values

No obvious correlation between prestrain levels and resistivity can be determined from the plot. Thus the different resistivities may be due to discrepancies in the manufacturing process of the TC-5005.

A plot of the power consumption per unit mass versus electric field strength for the 100,100%, 150,150% and 200,200% prestrains of VHB-4910 is shown in Figure 11. Again the dielectric breakdown strength is visible on this plot. The power consumption of the material slowly increases until the breakdown regions are reached, after which an almost asymptotic increase in power consumption occurs. Therefore, for use in an artificial muscle actuator, it will be necessary to restrict the material to within the pre-breakdown region in order to control power consumption.

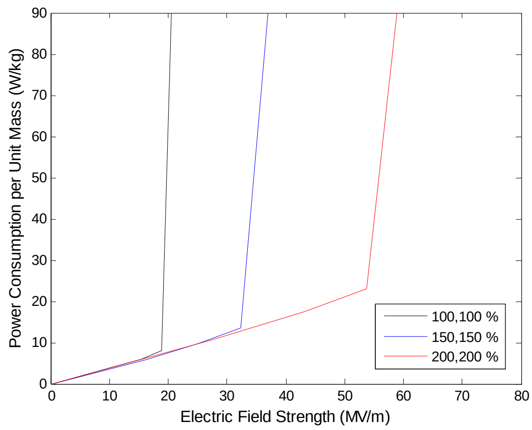

Figure 11: Power consumption plot of VHB-4910 at varying prestrain values

The plot of power consumption per unit mass versus electric field strength for the TC-5005 at various prestrains is shown in Figure 12. From the plot it is not possible to conclusively determine power consumption trends between different prestrains. It is also not possible to determine dielectric breakdown strengths for this material. Looking at the plot it can be seen that the trend in power consumption is almost quadratic in nature. This trend applies to all the different prestrains, and seems to indicate that prestraining does not have a significant impact on the power consumption of TC-5005.

Prior to breakdown the VHB-4910 material consumes less power than the TC-5005. However after breakdown the VHB-4910 consumes significantly more power than the TC-5005.

Individually, both materials are suitable candidates for use in artificial muscle actuator construction in terms of their electrical properties. However, provided that the VHB-4910 can be restricted to electric fields below its dielectric breakdown strength, it shows superior properties to the TC-5005.

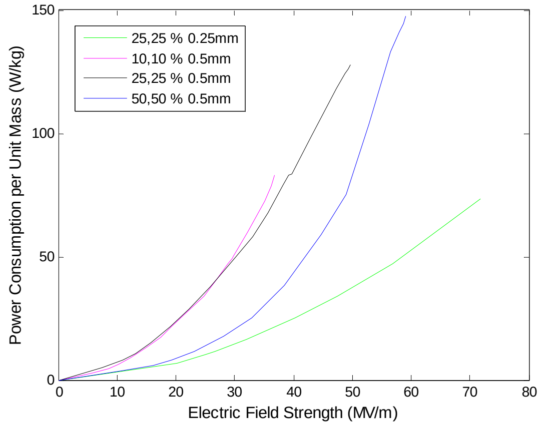

Figure 12: Power consumption plot of TC-5005 at varying thickness and prestrain values

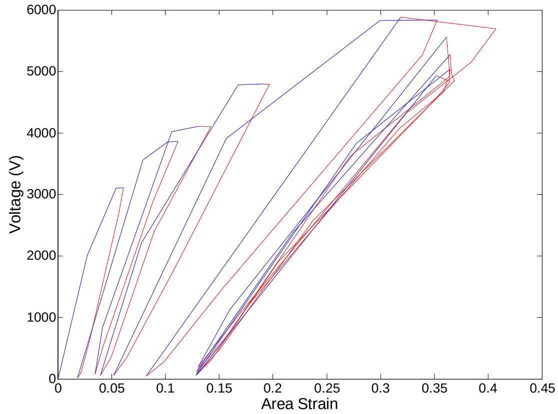

Figure 13: Hysteresis plot (including creep) of VHB-4910 with 100% prestrain in both directions. The blue lines indicate charging while the red lines indicate discharging

4.3 Hysteresis and Creep

The tests carried out provided enough data to produce basic hysteresis plots for both materials. Since the tests were not designed to specifically measure hysteresis, these results cannot be used to quantitatively measure the hysteresis of the dielectric elastomers. Rather, this data gives an indication of the significance of creep and hysteresis in each material.

Figure 13 shows the response of a piece of VHB-4910 to a stepped sequence of increasing voltage levels. Each step can be considered to be a single charge-discharge cycle of the material. Although this data came from the 100,100% prestrain test, all the tests with this material produced similar shaped responses. It is clear from the graph that VHB-4910 exhibits a significant amount of creep. When the dielectric elastomer is charged, it continues to deform under constant voltage, as shown by the flattened tops of the loops in the graph. Upon discharge, the elastomer does not relax fully, but maintains a degree of strain. However, when a specific voltage signal is repeated several times, the response follows the same path. This indicates that the observed creep could be a transient effect. Thus an actuator that uses VHB-4910 would need to be “warmed up” by running several charge-discharge cycles through it before it reaches its operating region.

To better observe the hysteresis effect of the VHB-4910, the response was also plotted after removing the creep bias. This is shown in Figure 14. It can be seen that the slope of the voltage-strain relationship decreases as the material is warmed up.

Figure 15 shows the response of a piece of TC-5005 to a stepped sequence of increasing voltage levels. Once again, this response was typical of all the TC-5005 tests. The direction of the loops in this graph is contrary to expectation, since it appears that the voltage is lagging behind the strain. Closer analysis shows that it is only the high voltage loops which exhibit this behaviour. Therefore, it is believed that this result was caused by the slow response time of the multimeter rather than any abnormal behaviour of the polymer. That is, it is likely that the measured voltages lag a little behind the actual voltages when the rate of change is too high. However, the discharging behaviour is still valid since the discharge cycle took longer than the charge cycle. This section of the plot shows that the TC-5005 followed the same general path on every discharge cycle. Thus, although the TC-5005 displayed some creep when charged, it always relaxed to its original shape when discharged. This means that an actuator that uses TC-5005 would not require warming up in the same manner as a VHB-4910 actuator would.

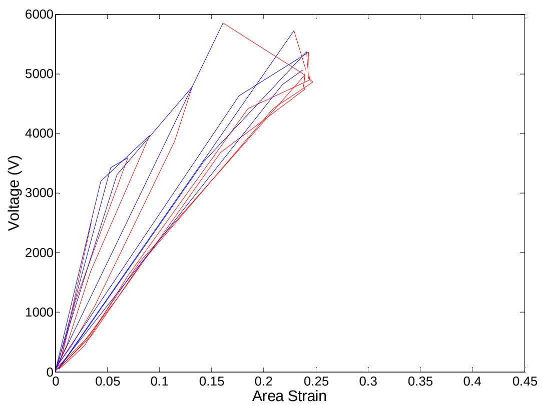

Figure 14: Hysteresis plot of VHB-4910 with 100% prestrain in both direction, with the effects of creep removed.

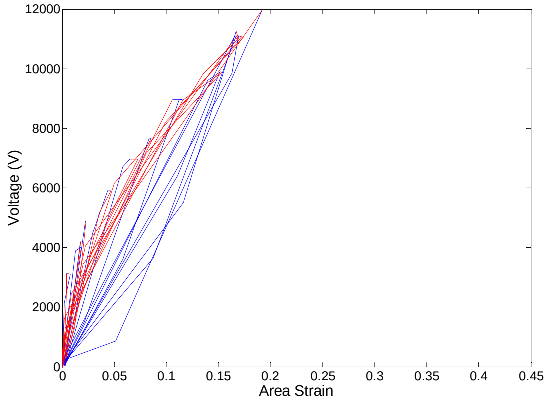

Figure 15: Hysteresis plot of TC-5005 with 50% prestrain in both directions. The blue lines indicate charging while the red lines indicate discharging.

These results show that there could be a significant amount of hysteresis in an actuator built using dielectric elastomers. Although this data is not of sufficient quality to measure the hysteresis, it is likely that the design of an actuator would have an effect on the behaviour. Thus a more detailed hysteresis test would be required once an actuator has been built in any case.

4.4 Errors and Inaccuracies

Several sources of possible errors and inaccuracies exist in the experimental procedures discussed in this paper. Due to limited resources and safety issues dealing with high voltages, the electrical equipment used in the experiments was not optimal for the test requirements. This introduced errors within the data collected. However, these errors are not significant enough to fundamentally alter the results presented.

Measurement of the voltage applied to the materials during testing was achieved using a high voltage probe connected up to a multimeter. Considerable difficulties are associated with the measurement of high voltages across materials with high resistance, due to the necessity of using voltage probes with even higher resistance values. Additionally, the display response time of the multimeters used was not fast enough to accurately display the applied voltage and current during the power supply charging cycle.

Errors were also associated with the manufacturing process. It was very difficult to mould the TC-5005 so that it was consistent and had uniform thickness across the entire sheet. Such inconsistencies may have introduced batch errors where materials moulded at different times, with the same specifications expressed different properties.

Other errors during testing included the rectangular electrode area and the prestraining of the materials. It is possible that circular electrode areas could produce more consistent results. Regarding prestraining, the percentage prestrains quoted in the figures are approximations. Furthermore, the applied prestrains were not necessarily exactly uniform in both directions. However, the results show that these errors were not important since the only significant effect of prestrain was an increase in dielectric breakdown strength.

5 Conclusions and Future Work

Both materials, the VHB-4910 and the TC-5005, have been shown to have the potential to be used in an artificial muscle actuator. The TC-5005 produced a maximum area strain of around 27%, which corresponds to a thickness strain of 21%. This places it at the lower end of the target range of 20 to 40% strain for an artificial muscle. In contrast, the VHB-4910 was able to produce area strains up to 95%, corresponding to thickness strains of up to 49%. Thus the VHB-4910 should be able to exceed the required strain for an artificial muscle actuator. However, under normal operating conditions (before breakdown occurred), the maximum area strain produced was around 45%, or 31% thickness strain.

Any actuator built using the VHB-4910 would be required to prestrain the material in order to raise the breakdown strength to a significant level. The most suitable current actuator design for the VHB-4910 is the spring roll actuator [Zhang *et al*., 2006]. In contrast, an actuator built using TC-5005 would not need to prestrain the material, provided a high enough voltage could be supplied to generate the desired electric field. Thus, an actuator could be constructed by folding a sheet of TC-5005 into a “continuous stack”, producing a device similar in principle to a piezoelectric stack actuator.

At similar electric field strengths, and before breakdown occurs, the VHB-4910 consumes less power than the TC-5005. In addition, since the VHB-4910 produced higher strains than the TC-5005 at comparable electric field strengths, an actuator that uses VHB-4910 would consume significantly less power than a TC-5005 actuator would in producing the same amount of strain.

Both materials displayed significant hysteresis which would need to be measured accurately once an actuator is built. The VHB-4910 also displayed a large amount of creep, and so a VHB-4910 actuator would need to be warmed up before it could be effectively used.

On balance, the VHB-4910 is a better candidate material for an artificial muscle actuator, due to its improved strain performance and lower power consumption. The performance of the TC-5005 could be improved through the application of larger electric fields or improved manufacturing methods. If this proved to be possible then TC-5005 could be a superior material since it does not require prestrain and does not display significant amounts of creep

The results presented in this paper are a preliminary study on materials that have the potential for use in artificial muscle actuators. The study could be extended to include more materials, such as NuSil Technology’s CF19-2186, provided improved manufacturing techniques can be developed. To avoid the errors and inaccuracies noted in this paper, the tests could be repeated with better quality equipment. In particular, a better quality power supply and better measurement equipment would improve the quality of the results. More targeted tests should be carried out to investigate properties such as the hysteresis and capacitance of the materials. Finally, an artificial muscle actuator built using these materials should be extensively tested since its properties may be different to those of the pure materials.

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