

Separator Membranes Produced from Polymers by Electrospinning for Applications in Electrical Double Layer Capacitors

Summer Undergraduate Fellowship in Sensor Technologies

Matt Biggers (Biomedical Engineering) – University of North Carolina at Chapel Hill

Advisors: Dr. Jorge Santiago and Dr. Rocío Cardona

ABSTRACT

Electrochemical capacitors are able to achieve high levels of capacitance and store large amounts of charge due to the ample availability of surface area. The porous separator membrane that separates the electrodes of an electrochemical capacitor allows ions to diffuse across to the opposite electrode, without recombination, when voltage is applied. This paper presents general information concerning electrochemical capacitors and electrospinning and presents the results from the research project intended to produce polymer which is environmentally-friendly and can be used as the separator membrane between super-capacitor electrodes. Various polymer solutions were made and electrospun onto a current collector forming a mat. Samples of the mats produced could then be analyzed based upon such characteristics as viscosity, chemical attributes, and mechanical attributes. Samples of the mats produced through electrospinning were also tested to see if they could achieve a greater level of capacitance than the separator membranes currently used. 15% weight/volume poly-lactic acid produced the highest capacitance, along with 15% weight/volume poly-lactic acid mixed with 3.5% weight/volume poly (ethylene oxide) and 12 mg of silver powder. The set-up that proved most useful for electrospinning these mats, was to electrospin the poly-lactic acid and poly (ethylene oxide) combination in layers using a dual-syringe pump.

Table of Contents

Title and Author Information.....	
Abstract.....	
Table of Contents.....	
1. Introduction.....	
2. Background.....	
2.1 Electrochemical Capacitors.....	
2.1.1 Electrochemical Double-Layer Capacitors.....	
2.1.2 Pseudo-capacitors.....	
2.1.3 Hybrid Capacitors.....	
2.2 Electrospinning.....	
3. Materials and Methods.....	
3.1 Chemical Materials.....	
3.2 Instrumentation.....	
3.3 Solubility Test.....	
3.4 Polymer Solution Preparation.....	
3.5 Electrospinning Process.....	
3.6 Chemical Test.....	
3.7 Viscosity Test.....	
3.8 Electrochemical Test.....	
4. Results.....	
4.1 Solubility Test.....	
4.2 Electrospinning.....	
4.3 Rheology.....	
4.4 Chemical Test.....	
4.5 Electrochemistry Test.....	
5. Conclusion.....	

6. Appendix.....	
7. Acknowledgments.....	
8. References.....	

1. INTRODUCTION

Scientists world-wide are searching for cheaper, more sustainable, and more environmentally-friendly forms of energy. With a push away from traditional fossil fuels, such as coal and petroleum, which are quickly being squandered, are not renewable, are costly, and produce harmful by-products, many have set their sights on electrical alternatives, such as the super-capacitor. Also known as electrochemical capacitors, super-capacitors are efficient energy storage devices and have found uses in many biomedical devices, mobile electronics, transportation, and aerospace systems [1,2].

Electrochemical capacitors are able to achieve high levels of capacitance and store large amounts of charge due to the ample availability of surface area. The porous separator membrane that separates the electrodes of an electrochemical capacitor allows ions to diffuse across to the opposite electrode, without recombination, when voltage is applied [1].

This paper presents general information concerning electrochemical capacitors and electrospinning and presents the results from the research project intended to produce polymer which is environmentally-friendly and can be used as the separator membrane between supercapacitor electrodes. Sect. 2 provides a background of electrochemical capacitors and electrospinning in order to contextualize this particular project. Sect. 3 gives the materials and instrumentation used throughout this project and the methodology behind their uses. Sect. 4 provides the results gained from various tests. Sect. 5 concludes this paper and project.

2. BACKGROUND

2.1 Electrochemical Capacitors

Capacitors consist of two electrodes separated by a thin, insulating dielectric material. Electrochemical capacitors, also known as ultracapacitors, are like conventional capacitors in that they store energy for a period of time before self-discharging that energy. Capacitance, C , is the ratio of stored positive charge, Q , to the applied voltage, V [1]:

$$C = \frac{Q}{V} \quad \text{Eq. 1}$$

The time it takes for capacitors to discharge can be controlled by varying certain factors, such as distance between electrodes and surface area. What makes super-capacitors “super” is that they are able to reach very high levels of capacitance by utilizing large surface area electrode materials and thin electrolytic dielectrics. As surface area, A , increases and the distance between electrodes, D , decreases, capacitance increases. The product of the dielectric constant of free space, ϵ_0 , and of the insulating material between electrodes, ϵ_r , creates a constant of proportionality [1]:

$$C = \frac{\epsilon_0 \epsilon_r A}{D} \quad \text{Eq. 2}$$

Super-capacitors are useful because they have an energy density, E , greater than conventional capacitors and a power density greater than batteries [1]:

$$E = \frac{CV^2}{2} \quad \text{Eq. 3}$$

In order to determine the power density of a capacitor, the external load resistance, R , which is usually accompanied with capacitors in an electrical circuit, must also be taken into account. The components of the capacitor, such as the electrodes, dielectric material, and current collector, also factor into this resistance and accumulate into a quantity called the equivalent series resistance (ESR). The ESR determines the voltage during capacitor discharge and the power of a capacitor can be determined as follows [1]:

$$P = \frac{V^2}{4 \times ESR} \quad \text{Eq. 4}$$

Other advantages over electrochemical batteries include shorter charging time, longer cycle-life, and longer shelf-life.

There are three types of super-capacitors and various sub-classes within these three classifications. The three types of super-capacitors include electrochemical double-layer capacitors (EDLCs), pseudo-capacitors, and hybrid capacitors [1].

2.1.1 Electrochemical Double-Layer Capacitors

EDLCs store charge electrostatically—a non-Faradaic process—and there is no transfer of charge between the electrode and electrolyte. They are constructed from two carbon-based electrodes, an electrolyte, and a separator membrane. As voltage is applied, charge accumulates on the electrode surfaces. Ions in the electrolyte solution diffuse across a separator to the electrode of opposite charge. The electrodes do not allow recombination of ions, producing a double layer of charge at each electrode. Because there is no transfer of charge, charge storage in EDLCs is highly reversible, allowing them to have high cycling stabilities. EDLCs can stably operate through as many as 10^6 cycles. In comparison, electrochemical batteries are usually limited to 10^3 cycles. The cycling stability of EDLCs makes them well-suited for uses in locations that are difficult for humans to reach, such as the deep sea or high-altitude environments [1].

Carbon electrodes have very high specific surface area (SSA), low cost, and are easy to manufacture. Different forms of carbon material that can be used to store charge in EDLCs are activated carbons, carbon nanotubes, and carbon aerogels. Activated carbons are the most

commonly used carbon-based electrodes due to their low cost and relatively high surface area. Activated carbons are composed of a complex structure of differently sized micropores ($< 20 \text{ \AA}$ wide), mesopores ($20\text{-}500 \text{ \AA}$ wide), and macropores ($> 500 \text{ \AA}$ wide). Research has shown that larger pore size is correlated with higher power density and smaller pore size is correlated with higher energy density. As binderless electrodes, carbon aerogels have a low ESR. Because of their continuous network of conductive carbon nanoparticles and mesopores and their ability to bond chemically to the current collector, adhesive binding agent is not required. Carbon nanotubes utilize an entangled mat with an open, interconnected network of mesopores which allows continuous charge distribution that uses almost all the available surface area [1].

2.1.2 Pseudo-capacitors

Pseudo-capacitors undergo Faradaic processes in order to store charge. Faradaic processes involve the transfer of charge between electrode and electrolyte using chemical mechanisms, such as oxidation-reduction reactions, electrosorption, and intercalation processes. Faradaic processes allow pseudo-capacitors to obtain higher capacitances and energy densities than electrochemical double-layer capacitors. Pseudo-capacitors use two different types of electrode material to store charge: conducting polymers and metal oxides. Conducting polymers have high capacitance and conductivity and a low ESR and cost in comparison to carbon-based electrodes. However, the development of conducting polymer pseudo-capacitors has been limited due to cycling instability caused by the mechanical stress during oxidation-reduction reactions. Metal oxides have proved to be useful as electrode material due to their high conductivity. High capacitances, high energy and power densities, and a low ESR can be obtained using ruthenium oxide. However, the cost of ruthenium oxide has proved prohibitive [1].

2.1.3 Hybrid Capacitors

Hybrid capacitors try to combine the benefits of pseudo-capacitors and EDLCs into one capacitor. Like the other types of capacitors, hybrid capacitors are distinguished by their electrode configuration: composite, asymmetric, or battery-type. Composite electrodes combine carbon-based materials with conducting polymer or metal oxide. Composite electrodes are able to achieve high levels of capacitance and cycling stability. Asymmetric electrodes integrate an activated carbon negative electrode with a conducting polymer positive electrode. While negatively charged, conducting polymer electrodes lack efficiency. Asymmetric electrodes attempt to circumvent this problem by using negatively charged activated carbon electrodes. Battery-type electrodes couple an ultracapacitor electrode with a battery electrode. These types of hybrid capacitors hold great potential in bridging the gap between supercapacitors and batteries [1].

2.2 Electrospinning

Electrospinning is a process that produces continuous polymer fibers consisting of various diameters, ranging from 5 to 500 nm [3]. Electrospinning uses electric charge to draw very fine fibers from liquid polymer in a syringe onto a grounded current collector, stretching the viscoelastic solution in a uniaxial fashion. Electrospinning first began in the 1700s with observations of water behavior in the presence of electrostatics. In the late 1800s, electrodynamics was used to explain dielectric liquid excitation under electric charge, leading to the invention of electrospinning by J.F. Cooley and W.J. Morton in the early 1900s. Due to the slow spinning process, little research had been done pertaining to electrospinning prior to 1990. However, much research currently goes into the implementation and improvement of this ancient process [4].

When high electric voltage, usually above 5 kV, is applied to the liquid droplet coming from the syringe, the liquid becomes charged and the electrostatic repulsion overcomes the surface tension, stretching the liquid droplet. At a certain voltage a stream of liquid erupts from the tip of the syringe [4]. The point of eruption is known as the Taylor cone. During flight, the jet stream dries and is collected on a spinning, electrically grounded, current collector. There are numerous set-ups in order to conduct electrospinning. For instance, a stationary current collector can be used instead of a spinning one.

Electrospinning is very similar to the more common process of electrospraying. Electric fields form and accelerate liquid jets at the end of a capillary into a distorted, random conical shape onto a current collector. There are numerous materials available for electrospinning, such as polymers, composites, semiconductors, and ceramics. However, the most commonly spun materials are polymers [4].

Numerous factors go into the process of electrospinning, such as solution viscosity, solution conductivity, applied voltage, spinneret tip to collector distance, humidity, and pump rate. These parameters can be adjusted in order to achieve an acceptable mat. Extensive research has gone into exploring various parameters and their effects on the electrospinning process [4].

Electrospinning is useful for the purposes of this particular project because through electrospinning polymer mats can be produced that are evenly and randomly distributed with polymer nanofibers. The small, randomly distributed fibers effectively allow ions to permeate the membrane material without recombination.

3. MATERIALS AND METHODS

3.1 Chemical Materials

Acetonitrile, deionized water (dH₂O), chloroform, and acetone were obtained from Fisher Scientific, HPLC graded. Propylene carbonate (PC), polytetrafluoroethylene (PTFE) (60 wt. %

dispersion in water), and 0.5 M Sulfuric Acid (H_2SO_4) were obtained from Sigma-Aldrich, Inc. Ethanol (200 proof) was obtained from Decon Laboratories, Inc.

Poly (vinyl acetate) (PVAc) (M_w : 500,000), poly-lactic acid (PLA), poly (ethylene oxide) (PEO) (M_w : 900,000), poly (vinyl alcohol) (PVA) (99+% purity), polyacrylonitrile, polyvinylpyrrolidone (M_w : 10,000), and activated carbon (Darco G-60, -100 mesh, powder) were obtained from Sigma-Adrich, Inc. Silver flakes (99.9% purity, APS 4-8 micron) were obtained from Alfa Aesar. Silver nano powder (99.95% purity, 150 nm) was obtained from Inframat Advanced Materials. Large multi-walled carbon nanotubes (l-MWCNTs) (95% purity, 60-100 nm diameter, 5-15 μm length) and small multi-walled carbon nanotubes (s-MWCNTs) (95% purity, 30-50 nm diameter, 0.5-2 μm length) were obtained from Nanostructured and Amorphous Materials Inc.

3.2 Instrumentation

For electrospinning, a high voltage power supply was obtained Gamma High Voltage Research. A triple output DC power supply from Agilent was used to rotate the spinning current collector. The spinning current collector was obtained from a Senior Design Project by Edward Kaiser, Frederico Wang, and their advisor, Professor Jorge Santiago. A syringe pump was obtained from New Era Pump Systems, Inc. and from kd Scientific. The sp210iw dual syringe pump was obtained from WPI. 5 mL (6 mL) syringes were obtained from Norm-Ject. 21 gauge 3/2 Precision Glide needles were obtained from B-D. WD-40 was obtained from WD-40 Company.

For electrochemical measurements, a Bipotentiostat Model AFCBP1, from Pine Instrument Company, was used with two platinum (Pt) electrodes as current collectors and Ag/AgCl (NaCl 3M) reference electrode in a short configuration. The PineChem 2.8.0 computer program was obtained from Pine Research Instrumentation.

For viscosity testing, a Bohlin Gemini Advanced Rheometer was obtained from Malvern Instruments Ltd and used a cone upper plate with a 4° inclination and 40 mm diameter.

3.3 Solubility Test

A solubility test was conducted in order to determine which solutes could potentially be used to form a mat. The four solutes tested were PVAc, PVA, polyacrylonitrile, and polyvinylpyrrolidone. A small amount of solute was placed into four separate test tubes. Each test tube was then filled with 1 mL of one of four solvents: water, acetone, ethanol, or chloroform. Once the solution was made, it sat for 5 minutes. After that period of time, the amount of solute that had dissolved was recorded. If the solute was partially or not at all dissolved, the test tube was placed in heat for 2 minutes. After 2 minutes, whether or not the solute had dissolved was recorded. It was found that only PVAc was soluble at room temperature. Polyvinylpyrrolidone was soluble in heat; however, this was not useful because electrospinning the polymer solutions take place in room temperature.

The solubility of these various solutes had to be tested because only completely dissolved solutions can be used for electrospinning. Solid chemicals cannot be electrospun because they are too large to travel through the small syringe needle. Therefore, the solid chemicals must be turned into a liquid by being dissolved by a solvent. Electrospinning non-homogeneous solutions will cause random concentrations of chemicals and a non-homogeneous mat.

3.4 Polymer Solution Preparation

In order to make the polymer solution that would be electrospun into a mat, first, the amount of solute needed was calculated using the following equation:

$$\text{Amount of solute} = \text{Solution volume} \times \text{weight : volume ratio} \quad \text{Eq. 5}$$

The appropriate amount of solute was placed in a 12 mL vial. To the vial, 12 mL of solvent was added along with a magnetic stir bar in order to help stir the solution when placed on top of a hot plate. The solution was left on the hot plate for a day to allow the solute to completely dissolve.

3.5 Electrospinning Process

The electrospinning process was carried out using either the single-syringe pump or the dual-syringe pump. The single-syringe pump set-up can be viewed in Figure 1. The syringe pump was filled with the polymer solution and all air bubbles were removed from the syringe. The 21 gauge 3/2 Precision Glide Needle was attached to the syringe and the complex was fixed to the syringe pump. A piece of aluminum foil was folded over the needle so that it was as close to the tip as possible without blocking the tip opening. The aluminum foil allowed connection from the high-voltage power supply to the syringe both mechanically and electrically. The pump was adjusted so that the syringe needle was in the middle of the current collector at a distance of 4.5-12 cm from the center point of the current collector. WD-40 was applied to the surface of the current collector so that the mat could more easily be removed after electrospinning. The current collector was grounded and the positive lead of the high voltage power supply was fixed to the aluminum foil on the syringe needle. The pump was turned on and the dispense rate was set. The Triple Output DC Power Supply was turned on and set to 6.000 V. Once a drop of solution was visible at the tip of the needle, the high voltage power supply was turned on and set to 8-22 kV.

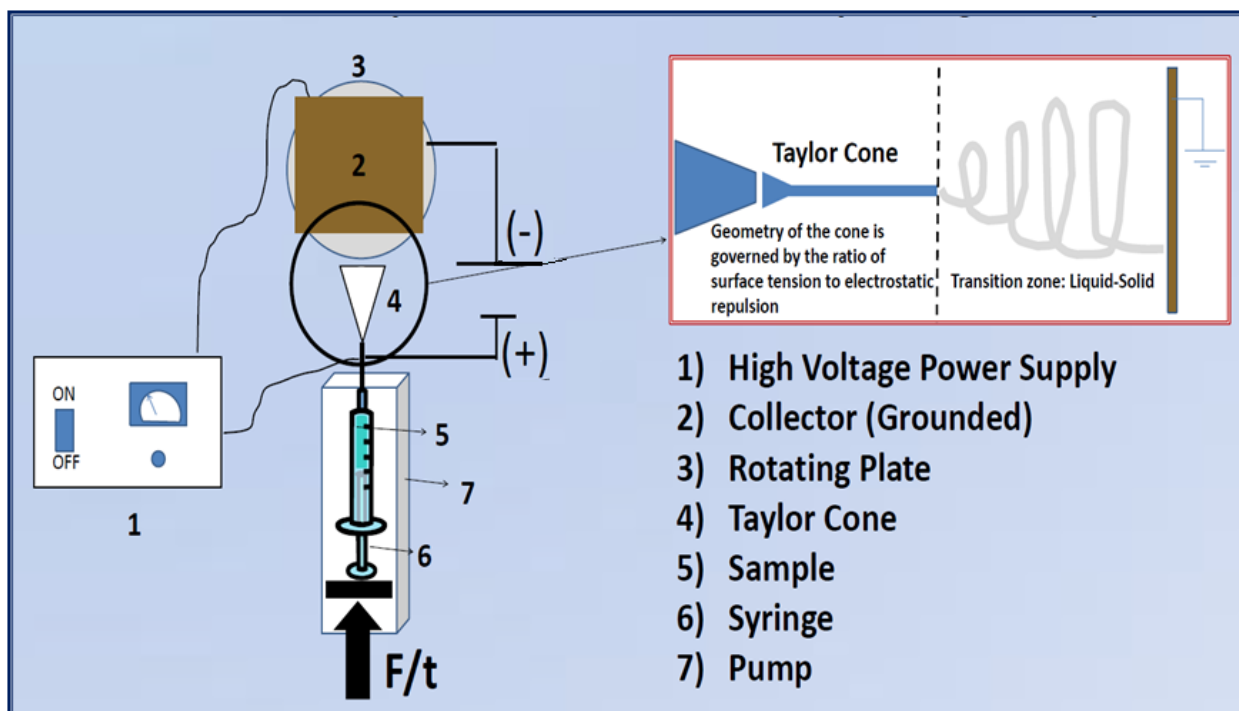


Figure 1. Single-syringe electrospinning set-up.

Once electrospinning was complete, the mat was removed and placed on aluminum foil. The dimensions of the mat were recorded and pieces were cut out to be used for various tests for characterization.

3.6 Chemical Test

Squares were cut out of mats in 0.5" x 0.5" dimensions and were used to observe how the mats reacted when submerged in various chemicals. The three chemicals used were dH_2O , acetonitrile, and propylene carbonate (PC). A sample was weighed and placed in a glass petri dish. Into the plate, 5 mL of one of the three chemicals was dispensed and the dish was covered. The sample was allowed to soak for 5 minutes. The sample was then removed and allowed to air-dry for 5 minutes before being weighed and measured. Each mat was tested with each chemical in this manner.

Performing a chemical test of the mats produced was important because it needed to be known whether or not the mat would withstand the electrolyte used in the electrochemical capacitor. If the separator membrane dissolves then the electrochemical capacitor would lose its capacitive capabilities and the mat would not be useful as separator membrane.

3.7 Viscosity Test

A small amount, approximately 1 mL, of polymer solution was dispensed in the rheometer between the upper plate and base. The viscosity of each polymer solution sample was measured as a function of time by comparing the viscosity of the sample as a function of shear stress. Each sample was subjected to a constant increase of shear stress over a period of approximately 10 minutes. The entire viscosity measurement for each sample took a total of 45 minutes and consisted of four 10 minute runs. After each run, the shear stress reset back to 0 Pa and increased from there. The temperature remained constant at 25.0 °C throughout the duration of the experiment.

3.8 Electrochemical Test

Small, circular samples were cut out of select mats and used to test their capacitive capabilities as a separator membrane. H₂SO₄ was dispensed onto one of the two Pt electrodes. A small circle of activated carbon, made from PTFE, ethanol, and activated carbon powder, was then placed on top of the H₂SO₄, making sure the Pt was completely covered. The separator membrane sample was then placed on top of the activated carbon and another activated carbon circle was placed on top of the separator membrane sample. More H₂SO₄ electrolyte was dispensed to fully cover the second activated carbon circle. Making sure the activated carbon and separator membrane fully covered the Pt, the second electrode was used to press the capacitor together. A positive lead connected the bipotentiostat to one electrode and a negative lead connected the bipotentiostat to the other electrode. The PineChem 2.8.0 program was used to measure the coulombic efficiency, percent of ions permeating the separator membrane, of the sample using AC voltage at a scan rate of 10, 25, 50, 100, 200, 500, 1000, 2000, 2500, 5000, and 10000 mV/s. Four sweeps of each sample were taken at three different voltage windows: 0-0.5 V, 0-0.75 V, and 0-1.0 V. The second and third (first decreasing and second increasing) sweep were used in calculating coulombic efficiency. Using the coulombic efficiency percentage, the average capacitance and specific capacitance could be calculated for each sample at each scan rate and voltage. The specific capacitances were finally compared to that of Gore-Tex, a standard, commonly used material for separator membrane made of PTFE [5].

4. RESULTS

4.1 Solubility Test

The results of the solubility test showed that PVAc was the only solute that could be used for electrospinning solution out of the four solutes tested. Polyvinylpyrrolidone dissolved only once heat was applied so was not useful for our purposes since electrospinning would take place at room temperature. Neither PVA nor polyacrylonitrile dissolved at all. Table 1 shows the results of the solubility test for PVAc at room temperature. The solutions most commonly spun during this project were 15% PLA, 15/20% PLA, and 3.5% PEO. Table 2 in the Appendix displays all of the polymer solutions made for electrospinning.

Table 1. PVAc solubility test results at room temperature.

Poly (vinyl acetate) Room Temperature			
Solvent	Soluble	Slightly	Insoluble
Water			X
Acetone	X		
Ethanol			X
Chloroform	X		

4.2 Electrospinning

Through performing several electrospinning experiments and experimenting with various parameters, it was found that certain polymer solutions produced the densest and most evenly electrospun mats under certain, specific conditions. When PEO was spun by itself it tended to peel off from the current collector. It was believed that this may have been due to a chemical reaction with the WD-40. However, when WD-40 was not applied, the PEO continued to peel off (Figure 2). When PEO was spun simultaneously with PLA or on top of a layer of PLA, no peeling occurred. When PLA was spun, the Taylor cone tended to elongate and solidify from the needle tip. From the Taylor cone would be multiple fibers spinning onto the current collector, creating dendrites on the Taylor cone (Figure 3). In general, the electric field produced by the high voltage power supply between the syringe needle and the grounded current collector should be 1 V/cm:

$$\vec{E} = \frac{\text{Voltage (V)}}{\text{distance (cm)}} = 1 \text{ V/cm} \quad \text{Eq. 6}$$

However, the strength of the electric field was adjusted as needed upon observation of the fibers protruding from the Taylor cone. Table 3 in the Appendix displays all of the mats electrospun throughout the duration of the project and the parameters under which they were spun.

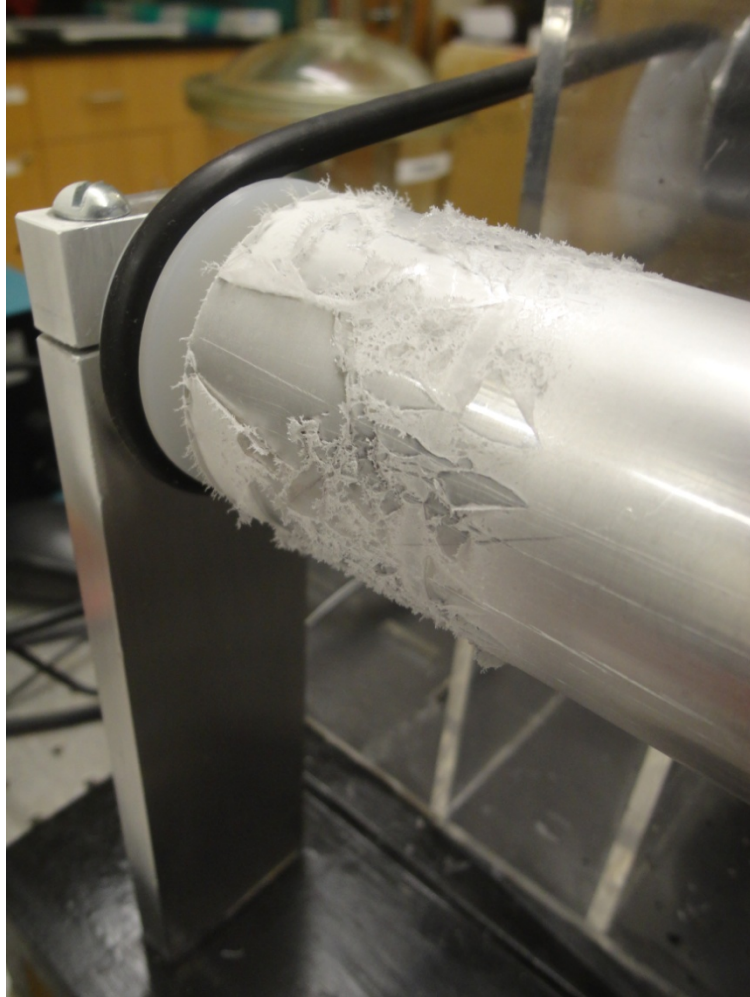


Figure 2. Electrospun PEO

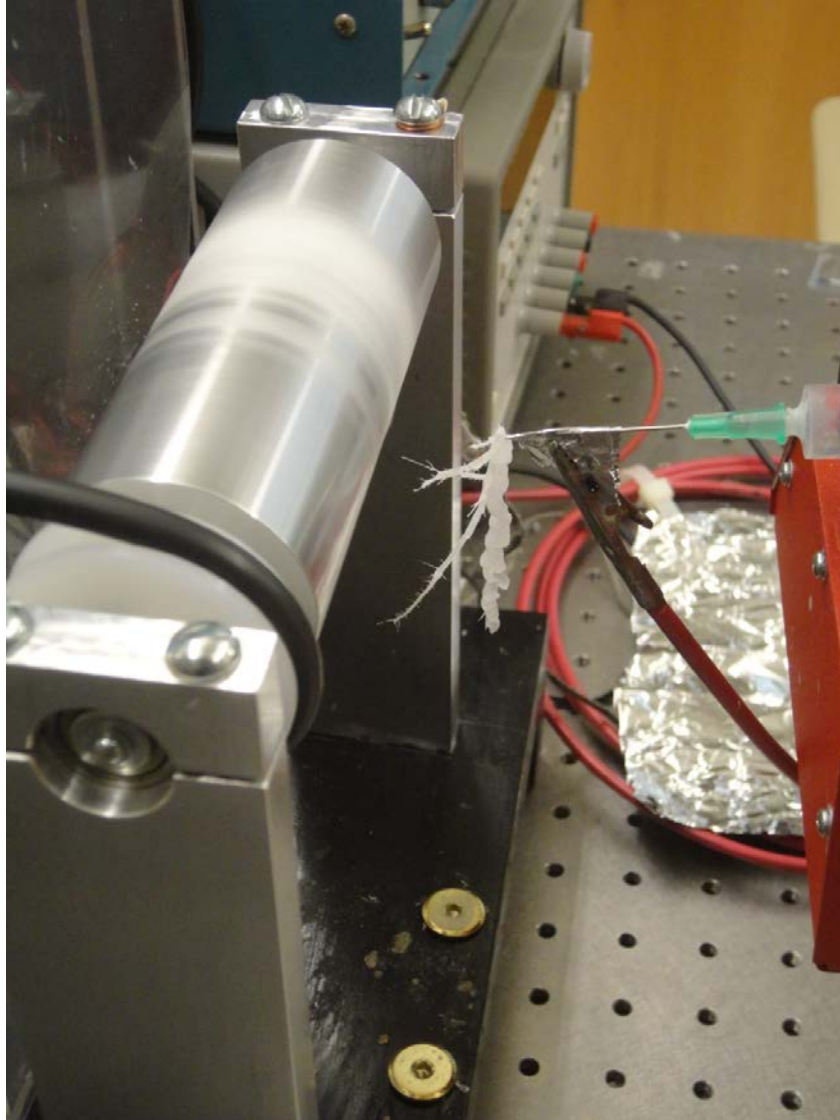


Figure 3. Electrospinning PLA

4.3 Rheology

The viscosity results for PLA and PVAc were not what were expected. For both PLA and PVAc, the third run exhibited very high viscosity levels and very high margins of error, shown in Table 4 and 5, respectively. The PEO however, produced results that were more in-line with expectations. The large standard deviations for PLA and PVAc can be attributed to the evaporation of solvent during the procedure. As solvent evaporated around the rim of the cone, the part of solution in contact with air, the rim of the test sample dried introducing additional stress and resistance to the test which skewed the viscosity test results. It is very likely that solvent also evaporated during the PEO viscosity tests; however, the PEO was not as affected by the effects of evaporation since its weight-to-volume ratio was so small: 3.5% for PEO compared to 15% for PLA and PVAc.

The viscosity of PEO remained fairly constant even with the addition of nanoparticles. However, adding s-MWCNTs caused the viscosity to decrease slightly and adding Ag powder caused the viscosity to increase, slightly. Adding s-MWCNTs introduces additional Van der Waals forces into the solution which make it easier for the solution molecules to slide across each other. Table 6 displays the viscosity results for PEO. The graph of viscosity as a function of shear stress and as a function of time for PEO can be seen in Figures 4 and 5, respectively. Based upon the results received, it was determined that 15% PLA, 3.5% PEO, and 15% PVAc could all be electrospun.

Table 4. PLA viscosity test results.

	15 % PLA	15 % PLA s-MWCNTs	15 % PLA l-MWCNTs	15 % PLA Ag Flakes	15 % PLA Ag Powder
Run 1	2.4 ±0.5	2.3 ±0.7	1.8 ±0.2	1.2 ±0.2	3.7 ±1.0
Run 2	5.1 ±0.5	78.5 ±49.6	7.3 ±1.1	18.8 ±14.7	8.9 ±1.9
Run 3	7.4 ±1.1	216.0 ±138.0	164.0 ± 51.1	102.0 ± 39.41	26.9 ± 10.9
Run 4	19.1 ±9.6	32.6 ±13.2	51.0 ± 0.6	85.2 ± 43.5	21.2 ± 5.0

Table 5. PVAc viscosity test results.

	15 % PVAc
Run 1	1.1 ±0.2
Run 2	4.7 ± 1.6
Run 3	10.1 ± 2.5
Run 4	13.1 ±3.5

Table 6. PEO viscosity test results.

	3.5 % PEO	3.5 % PEO s-MWCNTs	3.5 % PEO l-MWCNTs	3.5 % PEO Ag Flakes	3.5 % PEO Ag Powder
Run 1	1.5 ± 0.2	1.3 ± 0.2	1.6 ±0.2	1.4 ±0.3	2.0 ±0.4
Run 2	1.5 ± 0.2	1.3 ± 0.2	1.6 ±0.3	1.4 ±0.3	2.2 ±0.4
Run 3	1.5 ± 0.2	1.3 ± 0.2	1.6 ±0.3	1.4 ±0.3	2.3 ±0.4
Run 4	1.6 ± 0.1	1.3 ±0.2	1.7 ±0.3	1.8 ±0.1	2.5 ±0.5

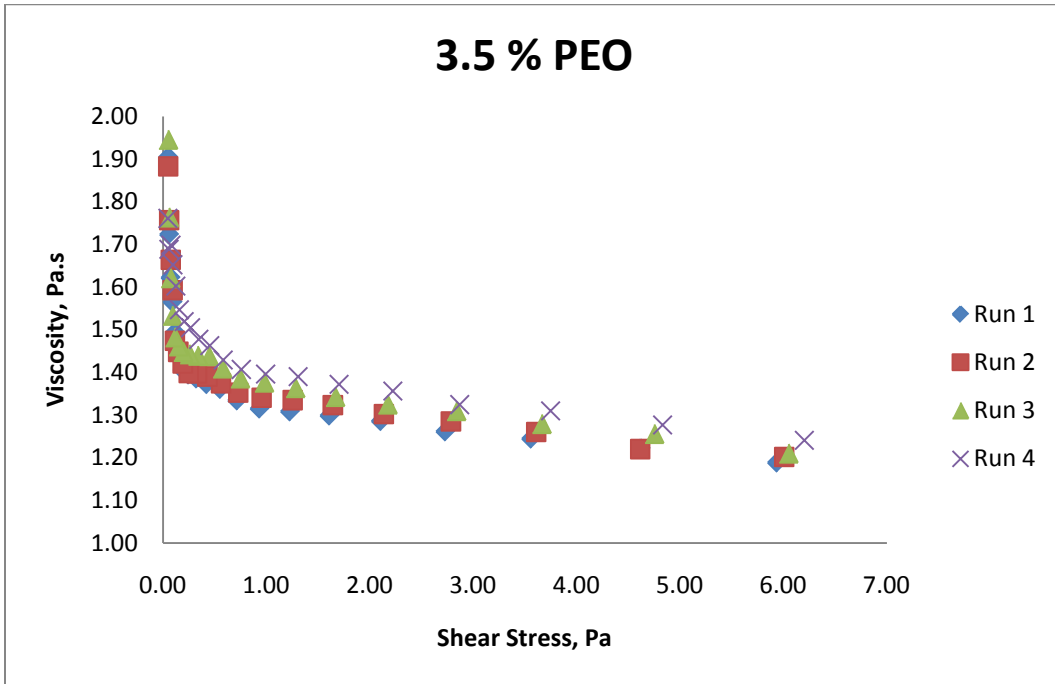


Figure 4. Graph of viscosity vs. shear stress for 3.5% PEO.

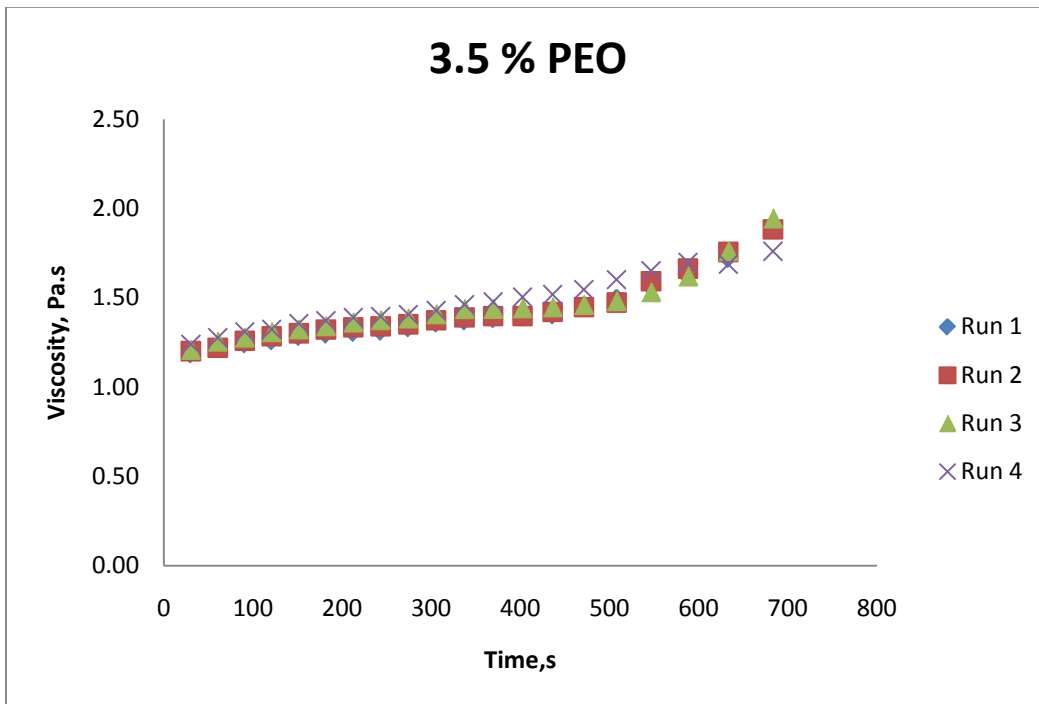


Figure 5. Graph of viscosity vs. time for 3.5% PEO.

4.4 Chemical Test

The chemical test suggested that the only chemical that would not destroy or damage the separator membranes was dH₂O. Acetonitrile instantly dissolved all of the chemical test samples upon contact and PC partially dissolved all of the samples (Table 7). Either PEO or PLA may have been soluble in PC, which would account for the partial dissolving of the chemical test sample membranes which all contained both PEO and PLA.

Table 7. Chemical test results for select mats.

Chemical Test					
Sample ID		Water	Acetonitrile	Propylene Carbonate	Comments
7-5-12-43	Weight Before (mg)	1.2	1.3	2.0	The sample completely dissolved upon contact when exposed to acetonitrile. The sample partially dissolved within seconds of exposure to PC and became clear.
	Weight After (mg)	1.7	N/A	7.4	
	Length (cm)	0.9	N/A	0.5	
	Width (cm)	0.9	N/A	0.5	
7-5-12-45	Weight Before (mg)	0.2	0.9	0.8	The sample completely dissolved when exposed to acetonitrile. The sample partially dissolved as soon as PC was applied.
	Weight After (mg)	0.8	N/A	3.0	
	Length (cm)	1.0	N/A	0.5	
	Width (cm)	1.0	N/A	0.5	
7-5-12-46	Weight Before (mg)	0.3	0.3	0.1	Completely dissolved when acetonitrile was applied. Anhydrous acetonitrile had the same affect. When PC was applied, the sample partially dissolved upon contact and completely dissolved within 3
	Weight After (mg)	0.8	N/A	N/A	
	Length (cm)	1.0	N/A	N/A	
	Width (cm)	1.1	N/A	N/A	

					minutes.
7-6-12-49	Weight Before (mg)	1.1	1.7	1.2	The sample partially dissolved when water was applied and when acetonitrile was applied and completely dissolved within 5 minutes of application. The sample partially dissolved into a thin clumped-up strip when PC was applied.
	Weight After (mg)	N/A	N/A	3.5	
	Length (cm)	N/A	N/A	1.5	
	Width (cm)	N/A	N/A	0.3	

4.5 Electrochemistry Test

Only two of the seven mat samples for the electrochemistry test displayed capacitive capabilities: 15% PLA & 3.5% PEO (Exp #43, 7-5-12-43) and 15% PLA w/ 12 mg Ag powder & 3.5% PEO w/ 12 mg Ag powder (Exp #65, 7-17-12-65). The other five samples either dissolved when subjected to the H₂SO₄ electrolyte or were too thin to provide any capacitive capabilities and conducted electrons in a linear fashion. As shown in Figures 4, 5, and 6, the Exp #43 sample mat had a specific capacitance comparable to, but slightly higher than that of Gor-Tex. The Exp #65 sample mat had a specific capacitance slightly higher than that of Exp #43, also shown in Figures 4, 5, and 6. Furthermore, the results remained constant at each voltage window: 0-0.5 V, 0-0.75 V, and 0-1.0 V.

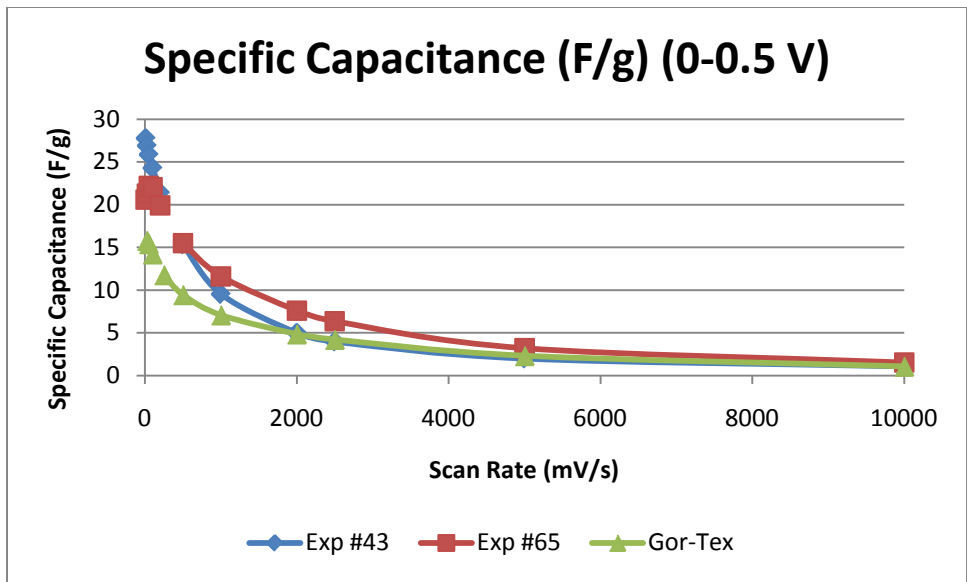


Figure 4. Specific capacitance in the 0-0.5 V window as a function of scan rate.

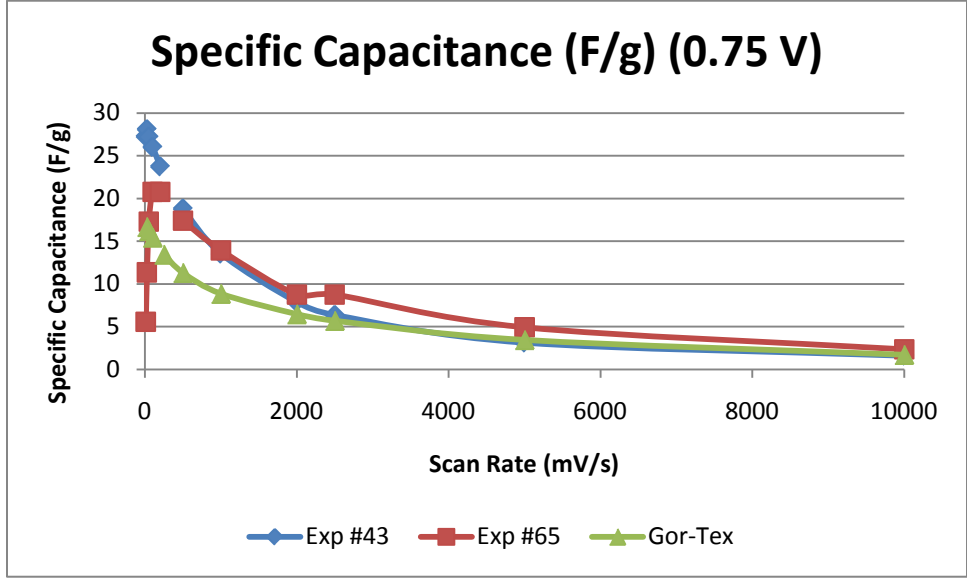


Figure 5. Specific capacitance in the 0-0.75 V window as a function of scan rate.

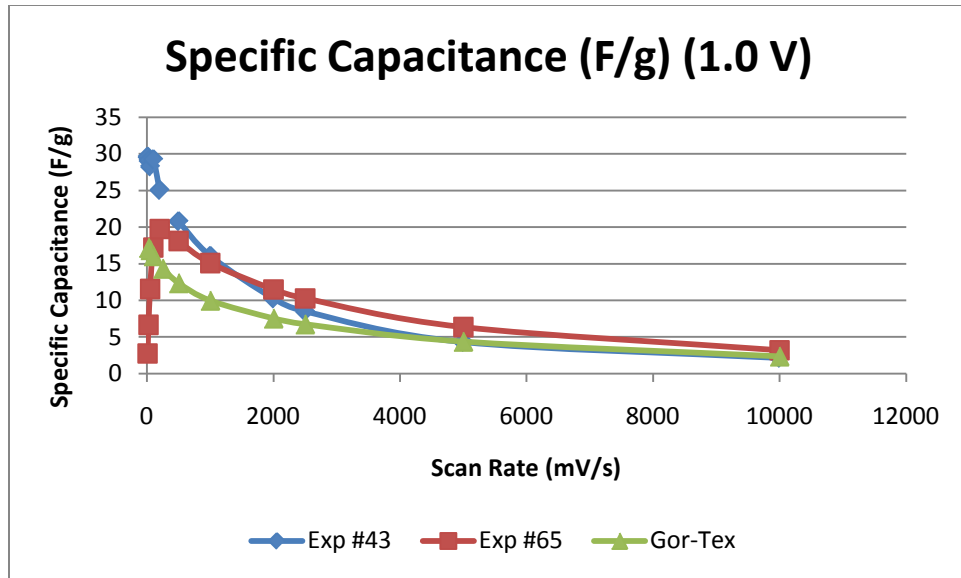


Figure 6. Specific capacitance in the 0-1.0 V window as a function of scan rate.

5. CONCLUSION

The electrochemistry tests for capacitance suggest that electrospun mats of 15% PLA with 12 mg Ag powder (1:3 acetone/chloroform) & 3.5% PEO with 12 mg Ag powder (dH₂O) produce a capacitance only slightly greater than that of Gore-Tex, the separator membrane most commonly used today. Electrospun mats of 15% PLA (1:3 acetone/chloroform) & 3.5% PEO (dH₂O) produce a level of capacitance greater than when Ag powder is added. The addition of nanoparticles was to enhance the mechanical properties of the mats. While the nanoparticles may have added to the mechanical resilience of the mats, they may also have made the mats more conductive, hindering their capacitive capabilities.

For the future, more experimenting must be done using the layering technique in electrospinning. Mats can be made electrospinning PEO on top of PLA in alternating layer fashion. These mats should also be tested electrochemically and compared to Gore-Tex and the mats already tested. Furthermore, mechanical testing should be performed on the mechanical samples cut out of the electrospun mats to test and physical resilience. Scanning electron microscopy should also be performed on the electrospun mats in order to get a closer observation of the polymer fibers.

6. APPENDIX

Table 2. All polymer solutions produced during the summer of 2012.

Polymer Solutions				
Solute (weight/volume)	Solvent	Theoretical Mass (g)	Experimental Mass (g)	Experimental Concentration (%)
15% Poly-lactic Acid (PLA)	1:3 acetate/chloroform	1.8	1.7831	14.9
15% PLA	1:3 acetate/chloroform	1.8	1.8271	15.2
15% Poly (vinyl acetate) (PVAc)	1:3 acetate/chloroform	1.8	1.8024	15.0
20% PVAc	1:3 acetate/chloroform	2.4	2.4030	20.0
50% PLA	1:3 acetate/chloroform	6.0	5.9856	49.9
50% PLA	1:3 acetate/chloroform	6.0	5.9619	49.7
20% PLA	1:3 acetate/chloroform	2.4	2.4222	20.2
20% PLA	1:3 acetate/chloroform	2.4	2.4001	20.0
15% PLA	1:3 acetate/chloroform	1.8	1.8056	15.0
15% PLA	1:3 acetate/chloroform	1.8	1.8053	15.0
20% PVAc	1:3 acetate/chloroform	2.4	2.4108	20.1
20% PVAc	1:3 acetate/chloroform	2.4	2.3918	19.9
15% PVAc	1:3 acetate/chloroform	1.8	1.8000	15.0

15% PVAc	1:3 acetate/chloroform	1.8	1.7998	15.0
15% PLA	1:3 acetate/chloroform	1.8	1.8168	15.1
20% PLA	1:3 acetate/chloroform	2.4	2.4110	20.1
15% PVAc	1:3 acetate/chloroform	1.8	1.7995	15.0
20% PVAc	1:3 acetate/chloroform	2.4	2.3945	20.0
7% Poly (ethylene oxide) (PO)	Deionized water (dH ₂ O)	0.84	0.8408	7.01
7% PO	Ethanol (EtOH)	0.84	0.8406	7.01
15% PVAc	1:3 acetate/chloroform	1.8	1.7944	15.0
15% PVAc	1:3 acetate/chloroform	1.8	1.7996	15.0
15% PLA	1:3 acetate/chloroform	1.8	1.8115	15.1
50/50 15% PLA/PVAc	1:3 acetate/chloroform	N/A	N/A	N/A
3.5% PO	1:1 EtOH/dH ₂ O	N/A	N/A	N/A
3.5% PO	dH ₂ O	0.42	0.4247	3.54
15% PLA/3.5% PO	acetone	1.8 (PLA), 0.42 (PO)	1.7930 (PLA), 0.2468 (PO)	14.9 (PLA), 2.06 (PO)
15% PLA	1:3 acetone/chloroform	1.8	1.8133	15.1
15% PLA	1:3 acetone/chloroform	1.8	1.8043	15.0
15% PLA	1:3 acetone/chloroform	1.8	1.8117	15.1
3.5% PEO	dH ₂ O	0.42	0.4228	3.52

3.5% PEO	dH ₂ O	0.42	0.4220	3.52
3.5% PEO	dH ₂ O	0.42	0.4190	3.49
15% PLA w/ 12 mg Large MWCNTs	1:3 acetone/chloroform	1.8	1.8049 g PLA w/ 11.9 mg LMWCNTs	15.0%; 0.992 mg/mL
15% PLA w/ 12 mg Large MWCNTs	1:3 acetone/chloroform	1.8	1.8070 g PLA w/ 12.9 mg LMWCNTs	15.1%; 1.08 mg/mL
15% PLA w/ 12 mg Large MWCNTs	1:3 acetone/chloroform	1.8	1.8327 g PLA w/ 12.6 mg LMWCNTs	15.3%; 1.05 mg/mL
3.5% PEO w/ 12 mg Large MWCNTs	dH ₂ O	0.42	0.4286 g PEO w/ 11.9 mg LMWCNTs	3.57%; 0.992 mg/mL
3.5% PEO w/ 12 mg Large MWCNTs	dH ₂ O	0.42	0.4202 g PEO w/ 11.9 mg LMWCNTs	3.50%; 0.992 mg/mL
3.5% PEO w/ 12 mg Large MWCNTs	dH ₂ O	0.42	0.4250 g PEO w/ 11.7 mg LMWCNTs	3.54%; 0.975 mg/mL
3.5% PEO w/ 12 mg Small MWCNTs	dH ₂ O	0.42	0.4185 g PEO w/ 12.4 mg SMWCNTs	3.49%; 1.03 mg/mL
3.5% PEO w/ 12 mg Small MWCNTs	dH ₂ O	0.42	0.4200 g PEO w/ 13.1 mg SMWCNTs	3.50%; 1.09 mg/mL
3.5% PEO w/ 12 mg Small MWCNTs	dH ₂ O	0.42	0.4185 g PEO w/ 16.5 mg SMWCNTs	3.49%; 1.38 mg/mL
15% PLA w/ 12 mg Large MWCNTs	1:3 acetone/chloroform	1.8	1.8008 g PLA w/ 12.1 mg SMWCNTs	15.0%; 1.01 mg/mL
15% PLA w/ 12 mg Large MWCNTs	1:3 acetone/chloroform	1.8	1.8018 g PLA w/ 13.2 mg SMWCNTs	15.0%; 1.10 mg/mL
15% PLA w/ 12	1:3	1.8	1.8253 g PLA	15.2%; 1.02

mg Large MWCNTs	acetone/chloroform		w/ 12.2 mg SMWCNTs	mg/mL
3.5% PEO	dH ₂ O	0.42	0.4196	3.50
3.5% PEO	dH ₂ O	0.42	0.4236	3.53
15% PLA	1:3 acetone/chloroform	1.8	1.8103	15.1
15% PLA	1:3 acetone/chloroform	1.8	1.7945	15.0
3.5% PEO w/ 12 mg Ag flakes	dH ₂ O	0.42	0.4210 g PEO w/ 11.5 mg Ag flakes	3.51%; 0.958 mg/mL
3.5% PEO w/ 12 mg Ag flakes	dH ₂ O	0.42	0.4187 g PEO w/ 12.0 mg Ag flakes	3.49%; 1.00 mg/mL
3.5% PEO w/ 12 mg Ag flakes	dH ₂ O	0.42	0.4219 g PEO w/ 12.0 mg Ag flakes	3.52%; 1.00 mg/mL
15% PLA w/ 12 mg Ag flakes	1:3 acetone/chloroform	1.8	1.8220 g PLA w/ 12.8 mg Ag flakes	15.2%; 1.07 mg/mL
15% PLA w/ 12 mg Ag flakes	1:3 acetone/chloroform	1.8	1.7969 g PLA w/ 12.1 mg Ag flakes	15.0%; 1.01 mg/mL
15% PLA w/ 12 mg Ag flakes	1:3 acetone/chloroform	1.8	1.7704 g PLA w/ 13.0 mg Ag flakes	14.8%; 1.08 mg/mL
3.5% PEO w/ 12 mg Ag powder	dH ₂ O	0.42	0.4182 g PEO w/ 13.2 mg Ag powder	3.49%; 1.10 mg/mL
3.5% PEO w/ 12 mg Ag powder	dH ₂ O	0.42	0.4191 g PEO w/ 11.6 mg Ag powder	3.49%; 0.967 mg/mL
3.5% PEO w/ 12 mg Ag powder	dH ₂ O	0.42	0.4202 g PEO w/ 17.8 mg Ag powder	3.50%; 1.48 mg/mL

15% PLA w/ 12 mg Ag powder	1:3 acetone/chloroform	1.8	1.8163 g PLA w/ 11.9 mg Ag powder	15.1%; 0.992 mg/mL
15% PLA w/ 12 mg Ag powder	1:3 acetone/chloroform	1.8	1.8126 g PLA w/ 12.4 mg Ag powder	15.1%; 1.03 mg/mL
15% PLA w/ 12 mg Ag powder	1:3 acetone/chloroform	1.8	1.8079 g PLA w/ 11.9 mg Ag powder	15.1%; 0.992 mg/mL

Table 3. All polymer experiments conducted the summer of 2012 and their parameters.

Polymer Experiments							
Experiment No.	Solution	Mat ID	Collect Time	Voltage (kV)	Distance (cm)	Rotation Velocity (V)	Pump Rate (mL/hr)
1	15% w/v PLA (1:3 acetone/chloroform)	6-6-12-1	1 hr	8	4.5	6.003	0.5
2	15% w/v PLA (1:3 acetone/chloroform)	6-6-12-2	2 hrs				
3	15% w/v PVAc (1:3 acetone/chloroform)	6-7-12-3	1 hr	8	4.5	6.001	0.5
4	15% w/v PVAc (1:3 acetone/chloroform)	6-7-12-4	1 hr	8	9	6.001	0.5
5	15% w/v PVAc (1:3 acetone/chloroform)	6-8-12-5	2 hrs	8	9	6.001	0.5
6	15% w/v PVAc (1:3 acetone/chloroform)	6-12-12-6	1 hr 20 min	8	9	5.999	0.5
7	20% w/v PVAc (1:3 acetone/chloroform)	6-12-12-7	44 min	8	9	6.000	0.5
8	20% w/v PVAc (1:3 acetone/chloroform)	6-13-12-8	1 hr	8	9	6.000	0.5
9	15% w/v PVAc (1:3 acetone/chloroform)	6-13-12-9	2 hrs	8	9	6.001	0.5

10	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-14- 12-10	1 hr	8	9	6.003	0.5
11	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-14- 12-11	1 hr	8	4.5	6.000	0.5
12	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-14- 12-12	1 hr	8	4.5	6.000	0.3
13	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-15- 12-13	1 hr	8	7	6.001	0.3
14	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-15- 12-14	1 hr	8	7	6.000	0.2
15	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-15- 12-15	40 min	16	10	6.001	0.5
16	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-15- 12-16	1 hr	16	10	6.000	0.5
17	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-18- 12-17	2 hrs	16	10	6.005	0.5
18	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-18- 12-18	2 hrs	16	10	6.000	0.5
19	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-19- 12-19	2 hrs	16	10	6.001	0.5
20	50/50 15% w/v PLA/PVAc (1:3 acetone/chloroform)	6-19- 12-20	1 hr 50 min	16	10	6.001	0.5
21	50/50 20% w/v PLA/PVAc (1:3 acetone/chloroform)	6-20- 12-21	1 hr	20	10	6.000	0.5
22	50/50 20% w/v	6-20-	30 min	9	4.5	6.001	0.5

	PLA/PVAc (1:3 acetone/chloroform)	12-22					
23	50/50 20% w/v PLA/PVAc (1:3 acetone/chloroform)	6-20-12-23	45 min	9	4.5	6.003	0.3
24	50/50 20% w/v PLA/PVAc (1:3 acetone/chloroform)	6-20-12-24		8	4.5	6.002	0.1
25	20% w/v PLA (1:3 acetone/chloroform)	6-21-12-25	1 hr	8	4.5	6.001	0.5
26	20% w/v PVAc (1:3 acetone/chloroform)	6-21-12-26	1 hr	8	4.5	6.001	0.5
27	20% w/v PVAc (1:3 acetone/chloroform)	6-22-12-27	2 hrs	8	4.5	6.001	0.5
28	20% w/v PLA (1:3 acetone/chloroform)	6-22-12-28	2 hrs	8	4.5	6.001	0.5
29	3.5% w/v PEO (1:1 EtOH/dH ₂ O)	6-25-12-29	1 hr	8	4.5	6.000	0.5
30	3.5% w/v PEO (1:1 EtOH/dH ₂ O)	6-26-12-30		8	9	6.002	0.5
31	3.5% w/v PEO (1:1 EtOH/dH ₂ O)	6-26-12-31	20 min	10	10	Stationary Cu	0.5
32	3.5% w/v PEO (dH ₂ O and evaporated EtOH)	6-26-12-32	2 hrs	10	10	Stationary Cu	0.5
33	3.5% w/v PEO (dH ₂ O and evaporated EtOH)	6-27-12-33	1 hr 25 min	10	10	Stationary Cu	0.5
34	3.5% w/v PEO (dH ₂ O)	6-28-12-34	1 hr	10	10	6.001	0.5
35	3.5% w/v PEO (dH ₂ O)	6-28-12-35	2 hrs	10	10	6.002	0.5
36	3.5% w/v PEO (dH ₂ O)	6-29-12-36	1 hr	10	10	6.001	0.5

37	15% w/v PLA (syringe 1) & 3.5% w/v PEO (dH ₂ O) (syringe 2)	7-2-12-37	5 min	17, 21	10	6.000	0.05
38	15% w/v PLA (syringe 1) & 3.5% w/v PEO (dH ₂ O) (syringe 2)	7-2-12-38		21, 17	10	6.001	0.005
39	15% w/v PLA/2.05% w/v PEO (acetone)	7-3-12-39	5 min	10	10	6.000	0.5
40	15% w/v PLA (syringe 1) & 3.5% w/v PEO (dH ₂ O) (syringe 2)	7-3-12-40	10 min	22, 15	10	6.000	0.025
41	15% w/v PLA (syringe 1) & 3.5% w/v PEO (dH ₂ O) (syringe 2)	7-3-12-41	8 min	15, 10	9	6.001	0.01
42	15% w/v PLA (syringe 1) & 3.5% w/v PEO (dH ₂ O) (syringe 2)	7-3-12-42	30 min	11, 10	8.5	6.001	0.01
43	15% w/v PLA (syringe 1) & 3.5% w/v PEO (dH ₂ O) (syringe 2)	7-5-12-43	1 hr	10, 15	10	6.000	0.01
44	15% w/v PLA (1:3 acetone/chloroform)	7-5-12-44	20 min	8	4.5	6.001	0.5
45	15% w/v PLA (1:3 acetone/chloroform)	7-5-12-45	1 hr	8	8	6.001	0.5
46	15% w/v PLA (1:3 acetone/chloroform)	7-5-12-46	2 hrs	8	8	6.001	0.4
47	3.5% w/v PEO (dH ₂ O)	7-6-12-47	1 hr	10	10	6.001	0.5
48	3.5% w/v PEO (dH ₂ O)	7-6-12-48	1 hr	10	10	6.005	0.5

49	3.5% w/v PEO (dH ₂ O)	7-6-12-49	1 hr	10	10	6.002	0.5
50	3.5% w/v PEO (dH ₂ O)	7-8-12-50	2 hrs	10	10	6.001	0.5
51	15% w/v PLA (syringe 1) & 3.5% w/v PEO (dH ₂ O) (syringe 2)	7-8-12-51	2 hrs	10, 15	10	6.001	0.5
52	15% w/v PLA w/ 12 mg LMWCNTs (syringe 1) & 3.5% w/v PEO w/ 12 mg LMWCNTs (dH ₂ O) (syringe 2)	7-9-12-52	1 hr	10, 10	10	6.001	1.5
53	15% w/v PLA w/ 12 mg LMWCNTs (syringe 1) & 3.5% w/v PEO w/ 12 mg LMWCNTs (dH ₂ O) (syringe 2)	7-9-12-53	1 hr	10, 10	10	6.001	1.5
54	15% w/v PLA w/ 12 mg LMWCNTs (syringe 1) & 3.5% w/v PEO w/ 12 mg LMWCNTs (dH ₂ O) (syringe 2)	7-9-12-54	1 hr	10, 10	12	6.001	1.5
55	15% w/v PLA w/ 12 mg LMWCNTs (syringe 1) & 3.5% w/v PEO w/ 12 mg LMWCNTs (dH ₂ O) (syringe 2)	7-11-12-55	2 hrs	10, 10	12	6.000	1.5
56	15% w/v PLA w/ 12 mg SMWCNTs (syringe 1) & 3.5% w/v PEO w/ 12 mg SMWCNTs (dH ₂ O) (syringe 2)	7-11-12-56	1 hr	10, 10	12	6.001	1.5
57	15% w/v PLA w/ 12 mg SMWCNTs	7-11-	1 hr	8, 10	10	6.001	1.5

	(syringe 1) & 3.5% w/v PEO w/ 12 mg SMWCNTs (dH ₂ O) (syringe 2)	12-57					
58	15% w/v PLA w/ 12 mg SMWCNTs (syringe 1) & 3.5% w/v PEO w/ 12 mg SMWCNTs (dH ₂ O) (syringe 2)	7-12-12-58	45 min	10, 10	12	6.001	1.5
59	15% w/v PLA w/ 12 mg SMWCNTs (syringe 1) & 3.5% w/v PEO w/ 12 mg SMWCNTs (dH ₂ O) (syringe 2)	7-12-12-59	1 hr	10, 10	12	6.001	1.5
60	15% w/v PLA w/ 12 mg SMWCNTs (syringe 1) & 3.5% w/v PEO w/ 12 mg SMWCNTs (dH ₂ O) (syringe 2)	7-12-12-60	2 hrs	10, 10	12	6.002	1.5
61	15% w/v PLA w/ 12 mg Ag flakes (syringe 1) & 3.5% w/v PEO w/ 12 mg Ag flakes (dH ₂ O) (syringe 2)	7-13-12-61		10, 10	12	6.000	1.5
62	15% w/v PLA w/ 12 mg Ag flakes (syringe 1) & 3.5% w/v PEO w/ 12 mg Ag flakes (dH ₂ O) (syringe 2)	7-13-12-62	1 hr	10, 10	12	6.000	1.5
63	15% w/v PLA w/ 12 mg Ag flakes (syringe 1) & 3.5% w/v PEO w/ 12 mg Ag flakes (dH ₂ O) (syringe 2)	7-13-12-63	1 hr	10, 10	12	6.001	1.5

64	15% w/v PLA w/ 12 mg Ag flakes (syringe 1) & 3.5% w/v PEO w/ 12 mg Ag flakes (dH ₂ O) (syringe 2)	7-17- 12-64	2 hrs	10, 10	12	6.001	1.5
65	15% w/v PLA w/ 12 mg Ag powder (syringe 1) & 3.5% w/v PEO w/ 12 mg Ag powder (dH ₂ O) (syringe 2)	7-17- 12-65	1 hr	10, 10	12	6.000	1.5
66	15% w/v PLA w/ 12 mg Ag powder (syringe 1) & 3.5% w/v PEO w/ 12 mg Ag powder (dH ₂ O) (syringe 2)	7-17- 12-66	2 hrs	10, 10	12	6.000	1.5
67	15% w/v PLA (layer 1, 3) & 3.5% w/v PEO (dH ₂ O) (layer 2, 4)	7-18- 12-67	1 hr/layer (4 hrs)	10, 10	12	6.000	1.5 (PLA), 1.4 (PEO)
68	15% w/v PLA (layer 1, 3) & 3.5% w/v PEO (dH ₂ O) (layer 2, 4)	7-19- 12-68	1 hr/layer (4 hrs)	10, 10	12	6.000	1.5 (PLA), 1.4 (PEO)
69	15% w/v PLA w/ 12 mg LMWCNTs (layer 1, 3) & 3.5% w/v PEO w/ 12 mg LMWCNTs (dH ₂ O) (layer 2, 4)	7-20- 12-69	1 hr/layer (4 hrs)	10, 10	12	6.000	1.5 (PLA), 1.4 (PEO)
70	15% w/v PLA w/ 12 mg SMWCNTs (layer 1, 3) & 3.5% w/v PEO w/ 12 mg SMWCNTs (dH ₂ O) (layer 2, 4)	7-23- 12-70	1 hr/layer (4 hrs)	10, 10	12	5.999	1.5
71	15% w/v PLA w/ 12 mg Ag flakes (layer 1, 3) & 3.5%	7-24- 12-71	1 hr/layer	10, 10	12	6.001	1.5

	w/v PEO w/ 12 mg Ag flakes (dH ₂ O) (layer 2, 4)		(4 hrs)				
72	15% w/v PLA w/ 12 mg Ag powder (layer 1, 3) & 3.5% w/v PEO w/ 12 mg Ag powder (dH ₂ O) (layer 2, 4)	7-25-12-72	1 hr/layer (4 hrs)	10, 10	12	6.000	1.5

7. ACKNOWLEDGEMENTS

I would like to thank Dr. Jorge Santiago and Dr. Rocío Cardona for leading this project, providing insight and knowledge about the topics and methodology, and giving me the opportunity to work in their research lab. I would like to thank Adam Fletcher, Rebecca Irizarry, Hitesh Sahoo, Esteban Villarreal, Tim Jones, and Raymond Xu for working with me this summer. I would also like to thank SUNFEST and NSF for the funding that allowed me to participate in this program.

8. REFERENCES

- [1] M. S. Halper and J. C. Ellenbogen, "Supercapacitors: A brief overview," The MITRE Corporation, McLean, Virginia, USA, Tech. Rep. 06-0667, March 2006. 2006.
- [2] P. Simon and Y. Gogotsi, "Materials for electrochemical capacitors," vol. 7, pp. 845-854, November 2008, 2008.
- [3] J. M. Deitzel, J. Kleinmeyer, D. Harris and N. C. Beck Tan, "The effect of processing variables on the morphology of electrospun nanofibers and textiles," Elsevier Science Ltd., Aberdeen, MD, March 20, 2000. 2000.
- [4] W. E. Teo and S. Ramakrishna, "A review on electrospinning design and nanofibre assemblies," IOP Publishing Ltd., Singapore, June 30, 2006. 2006.
- [5] R. M. Penner and C. R. Martin, "Ion Transporting Composite Membranes I. Nafion - Impregnated Gore - Tex," vol. 132, pp. 514, 1985.