

CHAPTER VIII

ELECTROMECHANICAL RESPONSE OF A SOFT AND FLEXIBLE ACTUATOR BASED ON A CROSS-LINKED POLY(DIMETHYL SILOXANE) NETWORK

8.1 Abstract

Electroviscoelastic characteristics of poly (dimethyl siloxane) (PDMS) networks containing camphorsulfonic acid (CSA) – doped polyaniline (PANI) particles were investigated. Samples were prepared by dispersing fine PANI particles in a cross-linked PDMS matrix. Rheological properties of the PANI/PDMS composites were studied in oscillatory shear mode to elucidate the effects of electric field strength, particle concentration, and operating temperature on the electromechanical response. On application of an electric field the storage modulus G' increases by an amount $\Delta G' \sim 10\text{-}50\%$, depending on PANI volume fraction, as the field strength is increased to 2 kV/mm. This increase in modulus is only partially reversible (about 37.5% recovery) on removal of the applied field, indicating that a quasi-permanent polarization is induced in the PANI particles. It is presumed that the increase in storage modulus originates in an electrostriction effect due to the attractive forces between polarized PANI particles embedded in the PDMS network. The temperature dependence of $\Delta G'$ shows a maximum at $T \sim 325$ °K, corresponding to the temperature range where the conductivity of PANI attains its maximum value. Finally, we report observations of the electromechanical response of a PANI/PDMS composite film, suspended in silicone oil between copper electrodes, which is manifested upon application of an electric field as a field-dependent deflection.

KEYWORDS: Electromechanical actuators, Poly(dimethyl siloxane), Conductive polymer, Polyaniline

8.2 Introduction

The exchange of electrical energy for mechanical energy in polymeric materials has long been of both theoretical and practical interest. Such interconversion is manifested in the piezoelectric and electrostriction phenomena that makes possible applications such as sensors and actuators, respectively, as well as the electrorheological (ER) effect, with potential applications as vibration dampers and clutches (Winslow, 1949). With respect to the latter, it is well known that suspensions of polymer particles with high dielectric constants dispersed in nonconducting oils stiffen rapidly, when subjected to electric fields on the order of 1 kV/mm. Such ER behavior, first studied extensively by Winslow (1949), is caused by alignment of the electrically polarized particles into strings, which span the gap between the electrodes (Krause and Bohon, 2001). Much research has focused on the development of ER fluids which exhibit a fast, reversible response (Klingenberg *et al.*, 1993). More recently, efforts have turned towards a new generation of stimuli-responsive composite elastomers, consisting of small magnetic- or electric-field-sensitive particles, dispersed in a highly elastic polymeric matrix (Shiga *et al.*, 1993, Bohon and Krause, 1998, Zrinyi *et al.*, 2000). Such field-responsive elastomers are often referred to as ER gels or, electroviscoelastic elastomers, since their viscoelastic properties vary in an electric field due to the interaction between the polarized particles (Shiga *et al.*, 1993).

While more complex mechanisms have been proposed, the point dipole model, in which polarization generates a point dipole moment within the particle, is most often used (Liu and Shaw, 2001). The interaction between dipoles on near neighbor particles results in a change in viscoelastic properties of the elastomeric matrix. Although the particles are locked within the elastomeric matrix and cannot agglomerate to form a fibrillar structure as in ER fluids (Liu and Shaw, 2001), the attractive interaction between dipoles on different particles may be expected to compress the elastomeric matrix (electrostriction), and cause a change in the viscoelastic properties. An appropriate balance between the particle interaction and the elastic modulus of the matrix is important for the electrostriction effect to manifest itself. If the elastic modulus of the matrix is larger than the sum of the

forces between particles, the electrostriction effect may not be observed macroscopically (Shiga, 1997). Therefore, blends with a softer matrix (Winslow, 1949) and higher particle content (Shiga *et al.*, 1993, Liu and Shaw, 2001, Mitsumata *et al.*, 2004) have been reported to show a larger electromechanical deformation.

In order to optimize the magnitude of the induced dipole, use of particles made from a semiconducting polymer, which typically can have a high intrinsic polarizability, is considered to be attractive (Block *et al.*, 1990). Examples include polyparaphenylene (Shiga *et al.*, 1993), poly(3-hexylthiophene) (Shiga *et al.*, 1995), and polyaniline (Winslow, 1949). PANI has several advantages, such as low density, ease of conductivity control, and thermal and environmental stability. PANI can be easily polymerized via an oxidative polymerization at relatively low temperatures, and can be doped from an insulating state to a conducting state using simple protonic acids. This allows a controlled variation in the particle dielectric constant and conductivity while keeping all other particle properties and suspension characteristics constant (Jang *et al.*, 2001).

The advantages of ER elastomers over ER fluids for certain applications include zero current leakage, no sedimentation of particles, the ability to generate the precise size and shape appropriate to a particular application, and perhaps the ability to achieve a higher dielectric constant [8]. Moreover, in contrast to ER fluids, since there is no change in morphology of the material during measurement, ER elastomers offer a new perspective into the mechanism of the ER effect (Liu and Shaw, 2001).

In this study, we explore the dynamic viscoelastic properties of composite gels, consisting of doped polyaniline (PANI) particles dispersed in a polydimethylsiloxane (PDMS) elastomer matrix, under electric fields. We focus on the effects of particle concentration, and matrix elasticity on the change in storage modulus. The dependence of the ER response on temperature, which is still unclear for polyaniline-based ER systems (Yanju *et al.*, 2001, Lee *et al.*, 1998), is also studied. Furthermore, reversibility of the ER response of the PANI/PDMS composites under cycles of on-off electrical switching is reported. Finally, we report preliminary data on an electroactuator response of a PANI/PDMS composite film.

7.1 Experimental

8.3.1 Materials

Aniline, C_6H_7N (AR grade, Merck) was vacuum-distilled and used as the monomer. Ammonium peroxydisulphate, $(NH_4)_2S_2O_8$ (AR grade, Merck) was used as the oxidant. (+) - Camphor-10-sulfonic acid, $C_{10}H_{16}O_4S$ (AR grade, Fluka); 37 % of Hydrochloric acid, HCl (AR grade, Labscan); 25 % of ammonium solution, NH_4OH (AR grade, Merck) and methanol, CH_3OH (AR grade, Labscan) were used as received. Poly(dimethylsiloxane), hydroxy terminated, $HO-[Si(CH_3)_2O]_n-H$ (viscosity 3,500 cSt, Aldrich) was used as a precursor of the cross-linked elastomeric matrix. Tetraethyl orthosilicate (TEOS), $Si(OC_2H_5)_4$ (AR grade, Aldrich) and Dibutyltin dilaurate (2EHSn), $CH_3[(CH_2)_{10}CO_2]_2Sn[(CH_2)_3CH_3]_2$ (AR grade, Aldrich) were used as a crosslinking agent and a catalyst, respectively.

8.3.2 Synthesis of PANI and PANI/PDMS Composite Preparation

PANI was synthesized via an oxidative coupling polymerization (Cao et al., 1989). 20.4 g of distilled aniline was added to 250 ml of 1.5M HCl aqueous solution and the mixture was vigorously stirred and cooled to 0-5 °C in a 3-necked round bottom flask. 250 ml of 1.5M HCl solution of 25.5 g $(NH_4)_2S_2O_8$ was then added dropwise into the flask within an hour. After all the oxidant was added, the reaction mixture was left stirring at 0-5 °C for 4 hours. The precipitated polyaniline was then washed with CH_3OH/H_2O mixture until the washing liquid was completely colorless. It was then dedoped by immersion in 3% NH_4OH , washed and dried at room temperature for 48 hours in vacuum. The emeraldine base was then suspended in a solution of CSA in water for 24 hrs at 40°C to increase its conductivity. The doping level was controlled by fixing the molar ratio N_{CSA}/N_{EB} at 5 (Koul et al., 2000). The filtrate was dried at room temperature for 48 hours in a vacuum oven, before passing through a 38 μm sieve shaker to control the particle size and its distribution. PANI/PDMS composite specimens were prepared by blending PANI particles with HO-PDMS and TEOS at a crosslinking agent to monomer ratio (C/M) of 0.053, using 2EHSn as the catalyst. The mixtures were poured in a mold and allowed to cure under vacuum for 24 hrs.

8.3.3 Characterization Methods

Fourier transform infrared spectroscopy (FT-IR, Bruker, Equinox 55/FRA 1065) was used to confirm the chemical structure of PANI. The spectrometer was operated in the transmission mode averaging 32 scans at a resolution of $\pm 4 \text{ cm}^{-1}$, covering a wavenumber range of $400\text{-}4000 \text{ cm}^{-1}$ using a deuterated triglycine sulfate detector. Optical grade KBr (Carlo Erba Reagent) was used as a background material. The samples were ground with KBr and pressed to form pellets.

An X-ray diffractometer (Rigaku model) was used to characterize the crystallinity of PANI. X-ray patterns were recorded on a Phillips PW 1830/00 No. DY 1241 Diffractometer. XRD analyses were performed on the undoped and CSA-doped polyaniline powder contained in a glass specimen holder and the diffraction patterns were examined between $2\theta = 5\text{-}60$ degrees.

The particle size distribution of PANI powder was determined by a particle size analyzer (Malvern, Master Sizer X).

Scanning electron microscopy (SEM, JEOL, JSM-5200-2AE) was performed at an acceleration voltage of 10 kV and a magnification of 350 to investigate the morphology of the CSA-doped PANI particles and of the composite containing the particles dispersed in the PDMS matrix. Prior to observation, samples were gold sputtered.

To determine the electrical conductivity, PANI powder was pressed into disk pellets using a hydraulic press (diameter of 25 mm and ~ 0.5 mm thick). The samples were then placed between 2 parallel plates under controlled temperature and the electrical conductivity was measured using an electrometer (Keithley, model 2410). The measurements were performed in the linear Ohmic regime where the specific conductivity values are independent of the applied DC voltage.

8.3.4 Rheological Measurements

Viscoelastic properties of the blends were investigated using a modified melt rheometer (ARES, Rheometric Scientific Inc.) with parallel plates (diameter of 25 mm) attached via insulating spacers to the transducer and motor. A DC electric field was applied across the gap between the plates by a function generator (GFG-8216A, Instek) and a high voltage amplifier (Model 609E-6, Trek).

Use of a DC field means that the particle polarization and particle interactions with each other and with the external field will be controlled by the particle and fluid conductivities rather than the particle and fluid permittivities. The samples were first checked for viscoelastic linearity by strain sweep tests. They were then presheared until their moduli reached steady state values. The electric field was initially applied for 20 minutes to obtain an equilibrium polarization state before each measurement was taken. Experiments were carried out in the frequency sweep mode ranging from 0.1 to 100 rad/s to investigate the effect of electric field strength on the storage and loss moduli, G' and G'' . All experiments were repeated twice, at each applied field strength, to confirm reproducibility.

8.4 Results and Discussion

8.4.1 Characterization of PANI

The FT-IR spectrum of PANI-CSA shows two additional peaks at 1730 and 1037 cm^{-1} , in addition to the five peaks characteristic of PANI, due to stretching of the C=O group and the sulfonic acid salt group, respectively (Furukawa *et al.*, 1988). Figure 7.1 shows the XRD pattern of PANI which indicates an increase in degree of crystallinity upon doping with CSA, due to the presence of CSA molecules in the PANI structure (Luzny and Banka, 2000).

8.4.2 Electromechanical Response of PANI / PDMS Blends

The effects of electric field strength, crosslink density of the matrices, particle concentration, and operating temperature on electromechanical response of the blends were explored. Particle volume fractions investigated are 0.02, 0.05, 0.10, 0.15 and 0.20, and operating temperatures are 300, 313, 323, 333 and 343 K. The mean diameter of the PANI particles is 23.5 μm with a standard deviation of 3.58 μm . As can be seen in the SEM micrograph in Figure 8.2a, the shapes of the CSA-doped PANI particles and their surfaces are quite irregular. However, the PANI particles are moderately well dispersed in the PDMS matrix as can be seen in the SEM micrograph of Fig 8.2b.

8.4.3 Temporal response

We first show the temporal response of a PANI/PDMS composite, consisting of CSA doped PANI particles embedded in a PDMS network at 10 vol%, to switching on and off of applied electric field, $E = 1000$ V/mm. As can be seen in Figure 3a, the modulus of the composite shows an abrupt increase from $G' = 57,000$ Pa to 65,000 Pa (~14 %) when the field is switched on. Interestingly, G' decreases from 65,000 Pa to 62,000 Pa after the field is switched off, i.e., approximately 37.5 % recovery. To understand this permanent change in mechanical property, the XRD and DG-TGA patterns of the CSA doped PANI particles were taken before and after being subjected to an electric field (~1kV/mm). No change in molecular structure or organization could be identified. Differential Scanning Calorimetry (DSC) was also used to investigate the possibility that the degree of cure of the elastomeric matrix might be increased by some internal heat built up caused by current leakage in the system. However, no new endothermic or exothermic peaks can be observed in 25-150 °C range.

An electric displacement - electric field (D-E) hysteresis loop was taken from a composite containing 10 vol % PANI particles and is shown in Figure 8.3b. The applied electric field strength was comparatively small, ~0.1 MV/m, compared to > 30MV/m used in similar experiments for ferroelectric ceramics, in order to prevent current leakage in the system. Figure 8.3b shows a distinct dielectric hysteresis, indicating that a measurable number of dipoles remaining in the composite after the field is switched off.

Based on the evidence from the D-E loop, and recalling the relatively high crystallinity of the PANI particles, we conjecture that the permanent change in electroviscous property is due to attractive interactions between the residual dipoles after the field is removed. Such behavior is generally observed in certain polycrystalline materials, when a large number of grain boundaries restrict the depolarization of dipoles below a certain temperature (Askeland, 1996). Utilization of such a permanent polarization in actuator applications is well established in ceramic materials, e.g. lead zirconate:lead titanate (PZT) (Furukawa, 1997), and in a class of ferroelectric polymers, viz. random copolymers of vinylidene fluoride with trifluoroethylene (VDF/TrFE) (Furukawa, 1997). However, to our knowledge, no

such effect has been reported in electroviscoelastic polymeric composites. A non-linear hysteresis in ER response has been observed in a polymethylaniline-based ER fluid (Han *et al.*, 2003).

8.4.4 Effect of Electric Field Strength and Particle Concentration

In the absence of an electric field, $E = 0$ V/mm, data shown in Fig 8.4a indicate that the PANI particles act as a reinforcing filler, since the storage shear modulus, G' , of the composite increases with increasing particle concentration: G' increases from 31599 to 97901 Pa (~210 %) as the PANI concentration is increased from 2 to 20 % v/v. Fig 8.4b shows that the modulus of the composites increases almost linearly with particle volume fraction before leveling off after 15 vol %. Figure 4b also shows the effects of electric field strength and particle concentration on the magnitude of the electroviscous response (characterized as the difference in modulus with the field on and off, $\Delta G' = G'_E - G'_{E=0}$) of the composites. $\Delta G'$ increases dramatically with increasing electric field strength, the composites with higher particle loading showing a greater electromechanical response; at a field strength of 2000V/mm, $\Delta G'$ is 417 Pa when the particle concentration is 2 % vol, and $\Delta G'$ increases to 26,243 Pa at a particle concentration of 20 % vol.

The microscopic attraction between the induced electric dipoles on the polyaniline particles evidently causes changes in the overall mechanical properties presumably via an electrostriction effect. Specimens with a higher volume fraction have stronger electrostatic interactions, since the average distance between particles is smaller, and these forces increase strongly as the interparticle spacing decreases (Sakurai *et al.*, 1999).

Interestingly, it can be noted that the dependence of storage modulus on particle concentration shows two distinct behaviors; G' increases relatively slowly with electric field strength at low particle concentration ($\Phi \leq 0.10$), whereas it abruptly increases at high field strength ($\Phi \geq 0.15$). Such a transition has been reported previously, and the characteristic crossover concentration Φ_c observed by us seems comparable to those found in the previous works; specifically, $\Phi_c \sim 0.10$ (Shiga *et al.*, 1993) and $\Phi_c \sim 0.08$ (Liu and Shaw, 2001). Below this crossover concentration, the number density of particles spanning the space between electrodes

is evidently not sufficient to create a strong enough electrostriction effect, resulting in a relatively weak electroviscoelastic effect (Shiga *et al.*, 1993, Liu and Shaw, 2001). Figure 8.4(b) further indicates that $\Delta G'$ levels off at high particle content ($\Phi = 0.20$). The onset of this plateau in $\Delta G'$ correlates with a leveling off in the increase in the modulus, G'_o , of the composite (Mitsumata *et al.*, 2004), which suggests there may be some agglomeration occurring from the polyaniline particles in this concentration range. Another contributing factor could be the screening of the dipolar interaction between the particles (Liu and Shaw, 2001).

In Figures 8.5a and 8.5b, respectively, $\Delta G'$ is plotted in log-log scale versus particle concentration and electric field strength, in order to compare the data with the equation proposed by Shiga in 1993:

$$\Delta G = (9/4)C\varepsilon_1\kappa^2 E^2 \quad (1)$$

where ΔG is the modulus response, C the particle concentration, E is the electric field strength, and ε_1 is the dielectric permittivity of the matrix. The parameter κ is defined in the presence of a dc electric field as

$$\kappa = (\sigma_2 - \sigma_1)/(\sigma_2 + 2\sigma_1) \quad (2)$$

where σ_1 and σ_2 are the conductivity values of matrix and particle, respectively. The slope of the dependence of $\Delta G'$ on particle concentration is found to be ~ 1.1 , which is close to the theoretical prediction. On the other hand, the slope indicating dependence on electric field strength is found to be around 0.4-0.6 at high field strengths and high concentrations. The discrepancy from the predicted scaling relation may arise from one or both of two factors: (a) the random distribution of particles, which is expected to remarkably diminish the attractive forces between PANI particles, since the induced dipoles attract each other when aligned end-to-end, but repel each other when side by side (Liu and Shaw, 2001, Shiga, 1997, Varga *et al.*, 2005); and (b) the relatively high conductivity of the PANI particles ($\sigma = 0.06$ S/cm at $T = 300$ K, see below), that theoretically may decrease the electric field

dependence of the electrostatic force from E_0^2 to E_0^1 due to an increase in conductivity of the matrix phase at high field strengths (Winslow, 1949, Parthasarathy and Klingerberg, 1996).

8.4.5 Effect of Operating Temperature

The storage modulus of the blend is found to increase with increasing temperature up to 323 K. This is a general property of rubber-like materials. In order to exclude the effect of matrix elasticity, $\Delta G' = G'(E) - G'(E=0)$ is plotted versus temperature in Fig 8.6. Evidently $\Delta G'$ initially increases with temperature up to 323 K: at $E = 2000$ V/mm, a composite containing 20 % v/v PANI particles exhibits $\Delta G' = 26,243$ Pa at 300 K and $\Delta G' = 129870$ Pa at 323 K. As the temperature is increased further to 343 K, however, $\Delta G'$ decreases to 40,295 Pa. Electrorheological fluids, that use polarizable particles made of polyaniline, are reported to have an optimum operating temperature, which occurs around $T = 320$ -335 K (Yanju et al., 2001, Lee et al., 1998). In ER fluids, a number of factors may contribute to the origin of temperature dependence: conductivities and polarizabilities of particle and medium, viscosity of the medium, Brownian motion of the particle strings and also adsorption/desorption of surfactant on the particle surfaces (Chotpattananont et al., 2004). In solid composites, it seems reasonable to assume that the temperature-dependence of the electroviscoelastic properties is determined predominantly by the magnitude of the particle-particle interaction. It seems most likely therefore that the maximum in the temperature dependence of $\Delta G'$ is due to fact that the conductivity (and hence polarizability) of polyaniline exhibits a maximum at around $T = 320$ -330 K (Mzenda et al., 2002). The existence of such a maximum in conductivity in our CSA-doped PANI is confirmed by experimental measurements, as shown in Figure 8.7, which are consistent with literature results (Mzenda et al., 2002).

8.4.6 Dielectrophoretic Behavior of a PANI/PDMS Actuator

Finally, the deflection of PANI/PDMS composite films in an electric field was investigated using the experimental set-up as shown in Figure 8. The PDMS/PANI films were suspended vertically in a silicon oil bath, with a dc electric field applied horizontally between two parallel flat copper electrodes, as shown in Figure 8. The amount of deflection at a specified field strength is defined by the

geometrical parameters A , B and θ , specified in the Figure 8.8. Figure 8.9 shows images of the bending of a PANI/PDMS composite film, $\sim 1 \times 2 \times 27$ mm, containing 10 vol% PANI particles, immersed in silicone oil (viscosity = 100 CSt), and observed at different electric field strengths. On applying the electric field, the free lower end of the film deflects towards the anode by an amount dependent on the field strength, indicating an attractive interaction between the applied field and the polarized PANI particles in the film. Gravitational force, and PDMS matrix elasticity, return the film approximately to its original position when the field is removed. As evident in Table 8.1, where we list values of the observed geometrical parameters, A , B , and $\theta \approx \arctan(A/B)$, there is a small displacement from the original null position of the film when the field is switched off. Also shown in Table 8.1 is the weight and length of the film specimen, as well as the weight at full deflection, where it is partially supported by the applied field. Reversal of the field polarity resulted in reversal of the direction of deflection of the film. Essentially identical results were obtained in experiments performed on a second 10 vol% PANI/PDMS composite film. It is presumed that the attractive force, F_{DEP} , exerted by the electric field, E_0 , on the film is dielectrophoretic in origin (Varga et al., 2005):

$$F_{DEP} = 2\pi\varepsilon_1 R^3 \kappa \nabla E_0^2 \quad (3)$$

where ε_1 is the dielectric permittivity of the PDMS matrix, R is the radius of the PANI particles, and κ is given by Eq. (2), and σ_1 and σ_2 are the conductivities of PDMS and PANI, respectively.

The above results can be compared with similar experiments performed on a 20 vol% deflection, as reflected in the values of A and θ which are slightly smaller for the film containing a higher volume fraction of PANI particles. The deflection angle θ is determined by the balance between the torque exerted by the dielectrophoretic force on the dipoles opposed by a torque exerted by gravity and a torque exerted by the elastic restoring force ($G_B \times$ the film cross-sectional area), where G_B is bending modulus. The net dielectrophoretic force should scale as the number of particles times F_{DEP} . Thus the torque balance equation is:

$$\begin{aligned}
& N_p \times (\text{film volume}) \times F_{\text{DEP}} \times (L/2) \cos\theta \\
& \approx G_B \times (\text{film cross-sectional area}) \times h\theta + mg(L/2)\sin\theta
\end{aligned} \tag{4}$$

where L is the film length and h is the film thickness, m is the film mass, and N_p is the number of PANI particles/ml. Realizing that the elastic restoring force substantially outweighs the gravitational force, utilizing eq. (4), it follows that:

$$\theta \approx \frac{N_p}{G'} \cdot \frac{\sigma_2 - \sigma_1}{\sigma_2 + 2\sigma_1} \tag{5}$$

Since the # of particle dipoles increases by $\sim \times 2$ and the modulus increases by $\sim 40\%$, and assuming the film volume remains approximately constant, it appears that the deflection A should increase by about 60% for 20 vol% PANI versus 10 vol% PANI fraction. Experimentally, we find that A decreases by about 10-20%. Based on eq. (6), it appears the discrepancy reflects a decrease in the effective dielectrophoretic force at higher particle concentration, due to a decrease in the effective conductivity contrast, $(\sigma_1 - \sigma_2)$, and/or screening of the interaction of the particles with the field.

Finally, we note that controlled experiments were performed on composite films containing 10 vol% and 20 vol% undoped PANI particles. Even at the highest field strength of 1,000 V/mm, the deflection in the film is barely perceptible ($\theta < 2^\circ$).

8.5 Conclusions

Composites films, consisting of camphorsulfonic acid (CSA) – doped polyaniline (PANI) particles dispersed in poly (dimethyl siloxane) (PDMS) networks were prepared and their electroviscoelastic behavior investigated as a function of electric field strength, particle concentration, and operating temperature. The storage modulus G' increases by an amount $\Delta G' \sim 10\text{-}50\%$, depending on PANI volume

fraction, when the applied field strength is increased to 2 kV/mm. This increase in modulus is only partially reversible (about 37.5% recovery) on the removal of the applied field. The magnitude of $\Delta G'$ increases with increasing particle content: $\Delta G' = 417$ Pa at a 2 % vol and increases to 26,243 Pa at a 20 % vol. The temperature dependence of $\Delta G''$ shows a maximum at $T \sim 325$ °K, where the temperature-dependent conductivity of PANI also exhibits a maximum value. We report the electromechanical response of a free standing PANI/PDMS composite film, containing 10 vol% PANI particles, when suspended in silicone oil between two flat parallel copper electrodes. When subjected to an electric field, the film exhibits a deflection, whose magnitude increases with increasing electric field strength, but decreases slightly when the particle concentration is increased to 20 vol%. The origin of the electromechanical response apparently resides in the conductivity-controlled polarization of the doped PANI, since the undoped PANI has negligible electromechanical effect.

8.6 Acknowledgements

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7.7 References

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Table 8.1 Effect of PANI Particle Volume Fraction on Dielectrophoretic Response of PANI/PDMS Composite Films

Sample	E (V/mm)	B (cm)	A(cm)	θ (degree)	
10 vol % PANI total weight = 0.0314 g total length = 2.75 cm mass = 0.01907 g	0	1.67	-	-	
	129	1.61	0.11	3.90	
	259	1.61	0.17	6.03	
	390	1.52	0.31	11.53	
	520	1.51	0.47	17.29	
	0	1.57	0.09	3.28	
	129	1.54	0.11	4.08	
	259	1.53	0.22	8.18	
	390	1.48	0.39	14.76	
	520	1.52	0.48	17.52	
	20 vol % PANI total weight = 0.0456 g total length = 2.8cm mass = 0.02720 g	0	1.68	-	-
		259	1.67	0.15	5.13
390		1.66	0.34	11.57	
520		1.66	0.35	11.91	
0		1.67	0.07	2.40	
259		1.67	0.15	5.13	
390		1.64	0.37	12.71	
520		1.61	0.38	13.28	

* For each sample, electric field strength was increased sequentially from zero to 520 V/mm and deflections were observed and measured; the experimental procedure was repeated for a second time using the same sample.

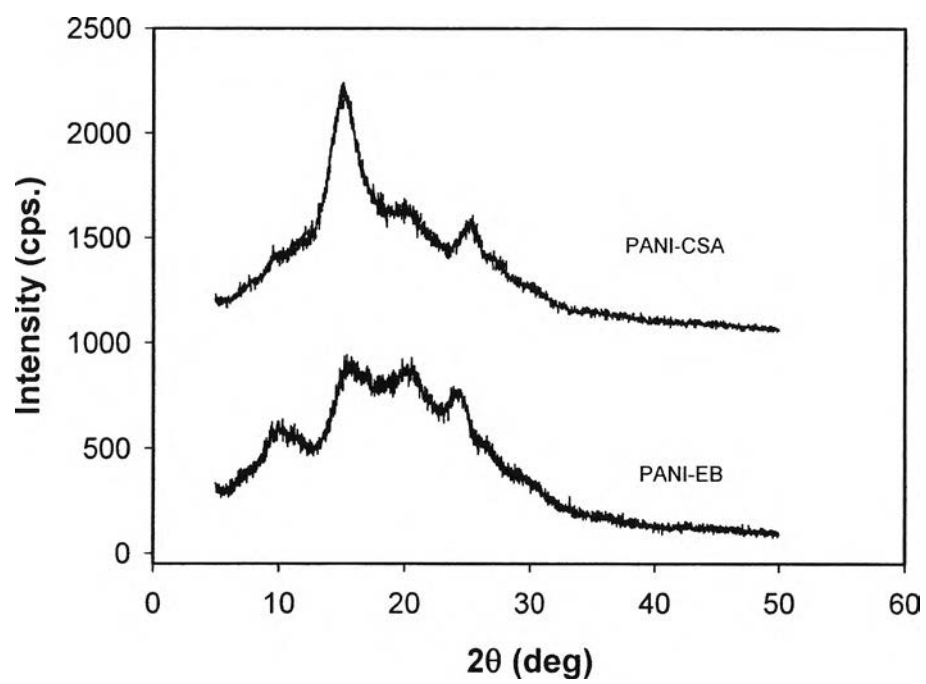
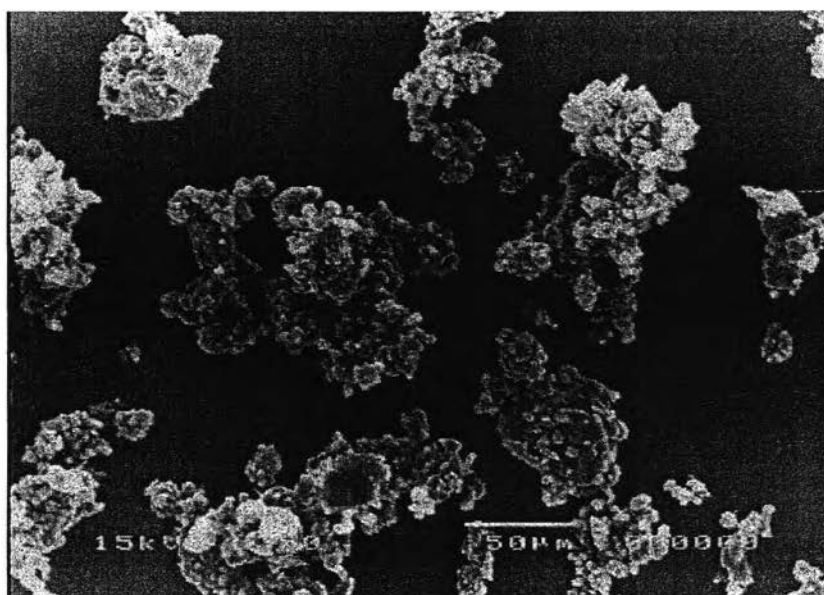


Figure 8.1 XRD patterns of undoped and CSA-doped polyaniline.



a)



b)

Figure 8.2 Scanning electron microscopy of: (a) CSA doped PANI particles, average particle size is 23.5 μm ; (b) PANI/PDMS composite containing 5 vol% PANI particles dispersed in a PDMS matrix ($C/M = 0.053$).

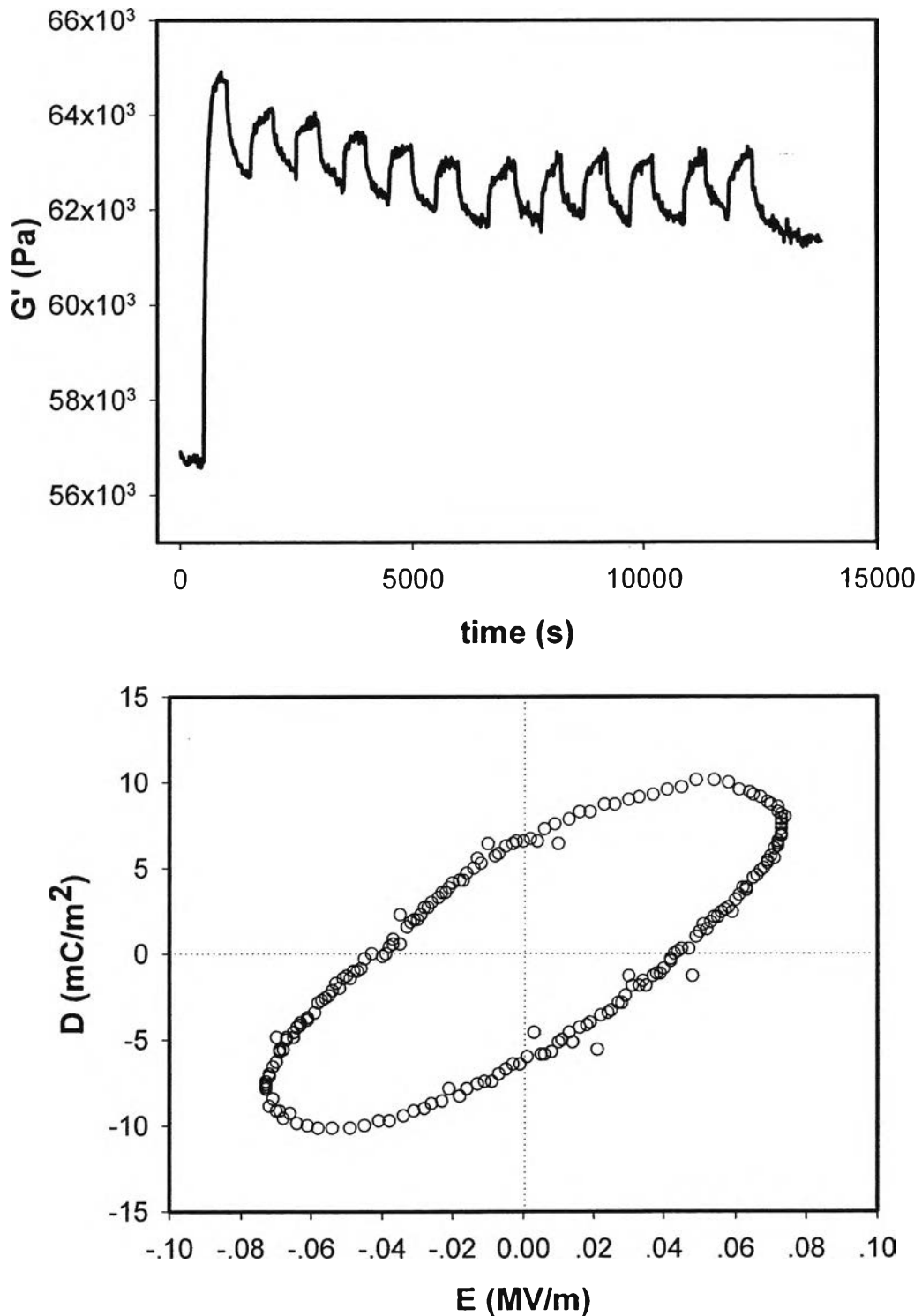


Figure 8.3 (a) Temporal ER switching response of PANI/PDMS composites containing 10 vol% CSA doped PANI particles at $E = 1\text{ kV/mm}$, $\omega = 1\text{ rad/s}$, $\gamma = 1\%$, temperature $27\text{ }^\circ\text{C}$; (b) D - E hysteresis loops for 10 %vol CSA doped PANI/PDMS.

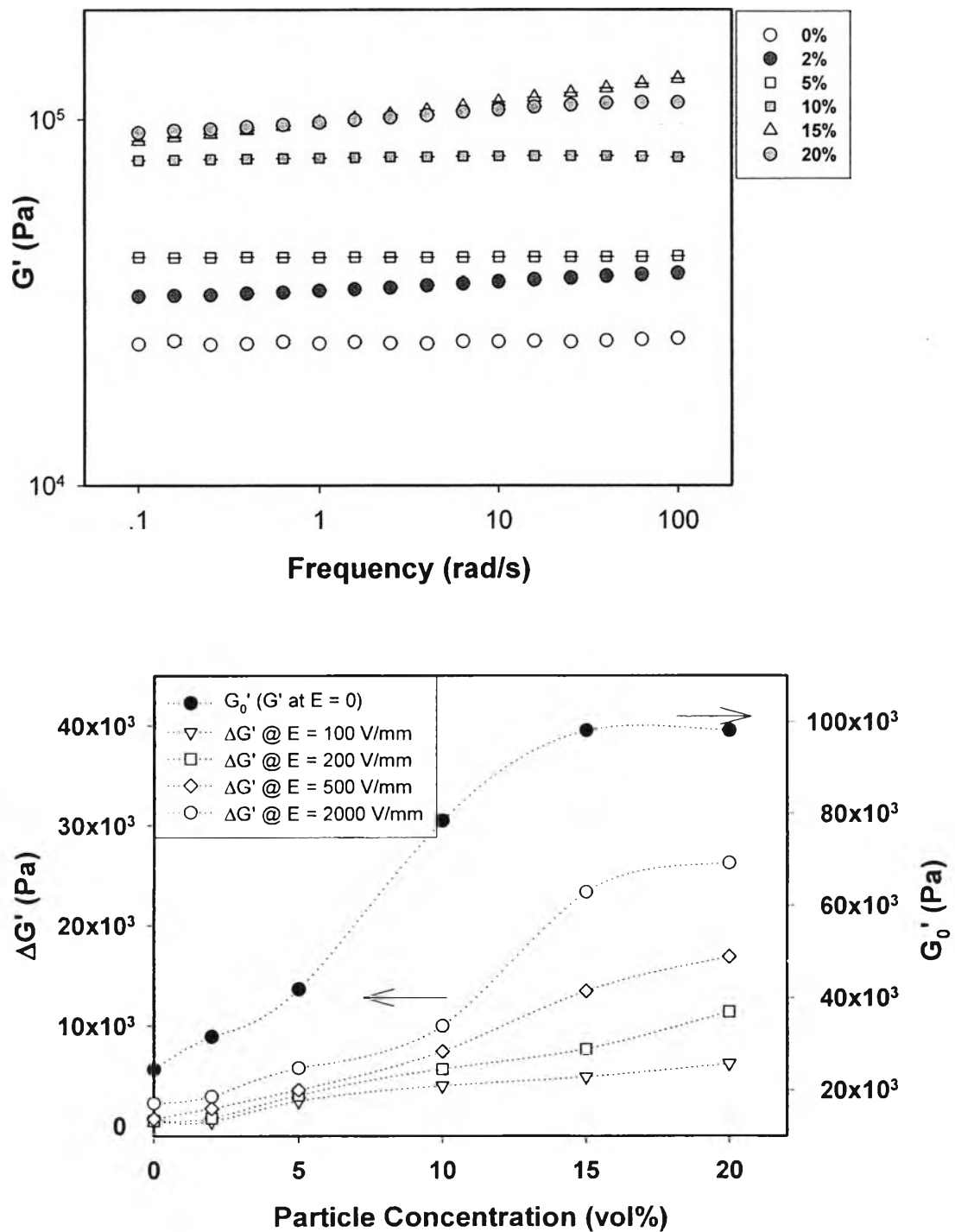


Figure 8.4 (a) Frequency dependence of storage modulus G' at zero electric field; (b) particle concentration dependence of G' and modulus change $\Delta G' = G'(E) - G'(E=0)$ (at $\omega = 1$ rad/s) of PANI/PDMS composites (C/M = 0.053) of different electric field strengths, measured at $T = 27$ °C.

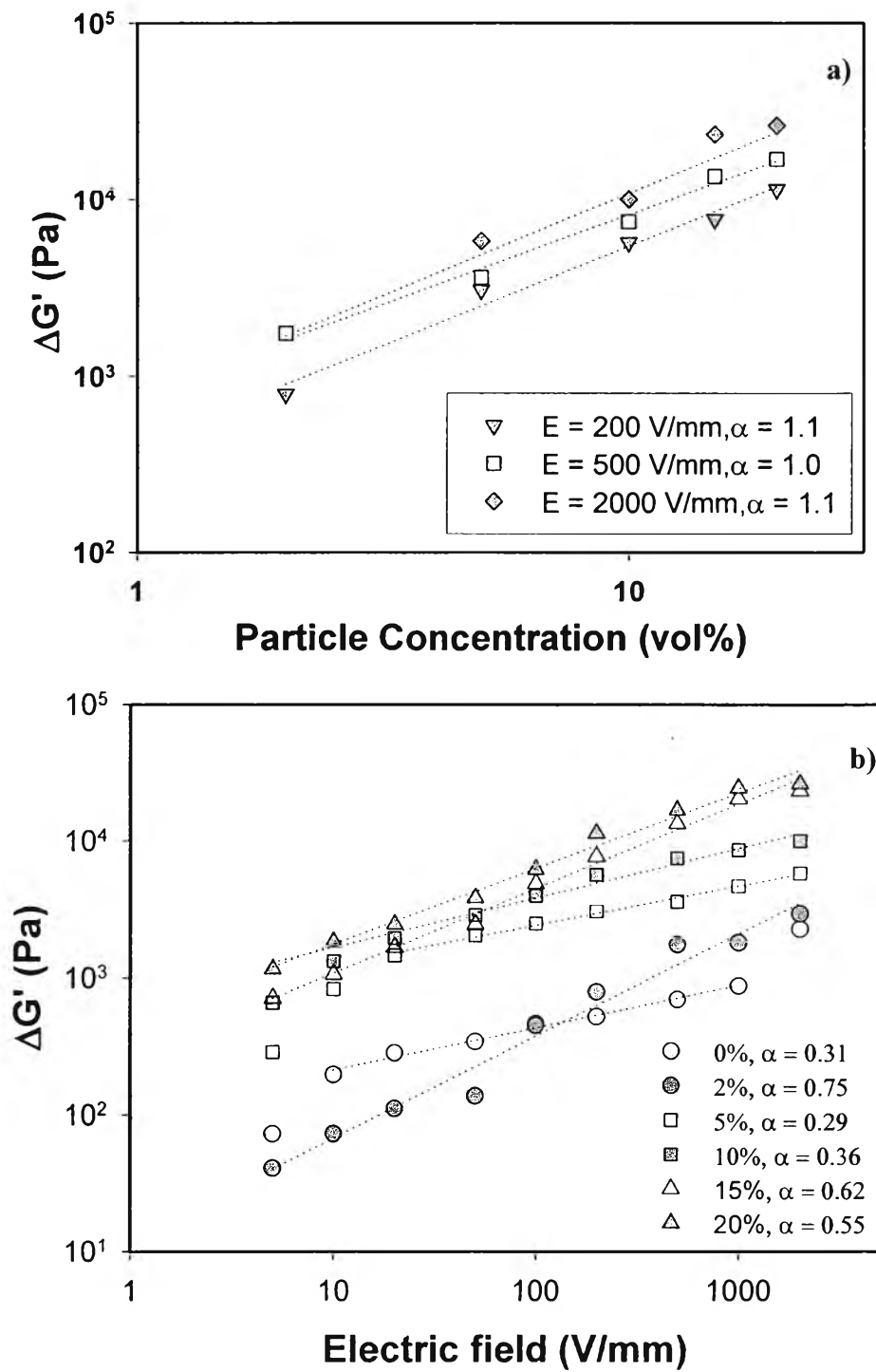


Figure 8.5 Dependence of $\Delta G' = G'(E) - G'(E=0)$ (at $\omega = 1$ rad/s) of PANI/PDMS composites on: (a) particle concentration; and (b) electric field strength, measured at $T = 27$ °C, and $C/M = 0.053$.

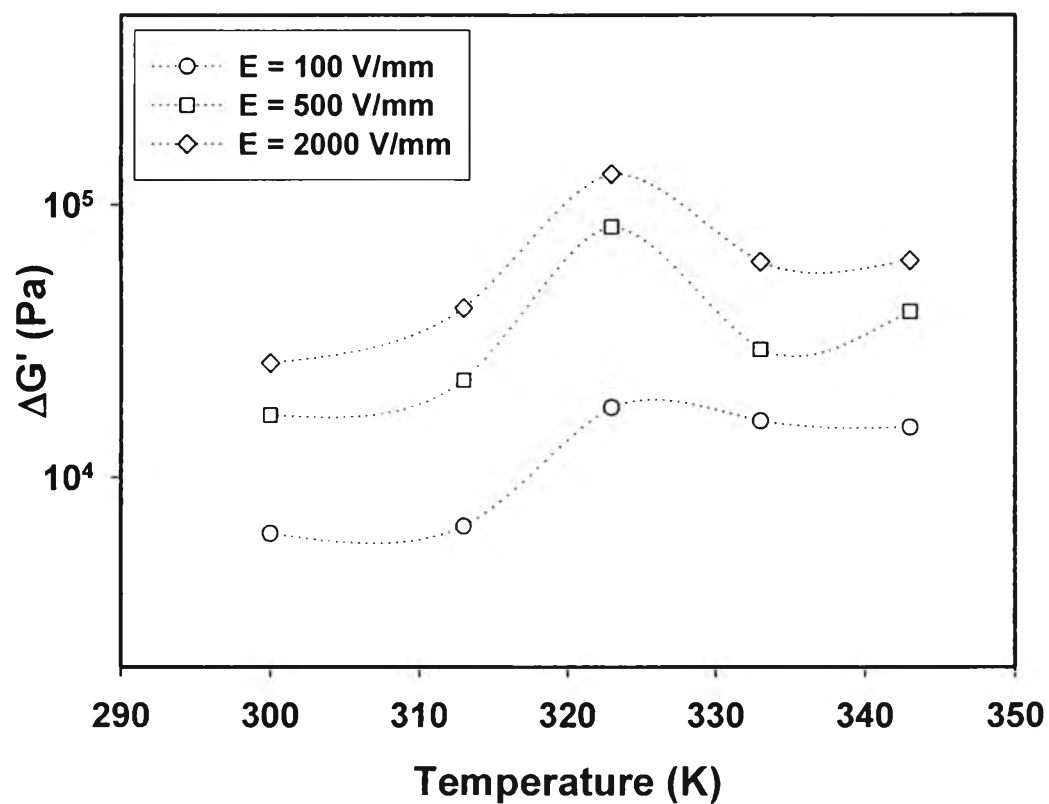


Figure 8.6 Temperature dependence of $\Delta G' = G'(E) - G'(E=0)$ (at $\omega = 1$ rad/s) for blends with particle concentration of 20 % v/v, $C/M = 0.053$, at various temperatures.

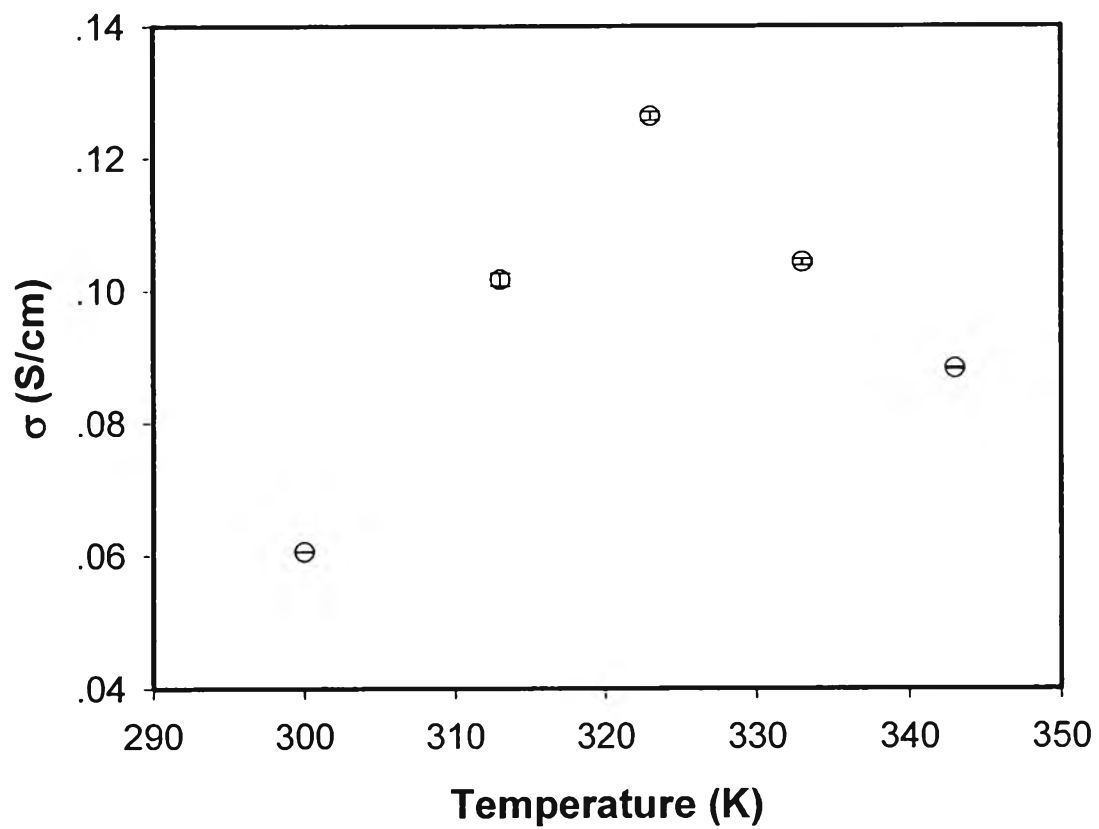


Figure 8.7 The dependence of PANI pellet conductivity on temperature.

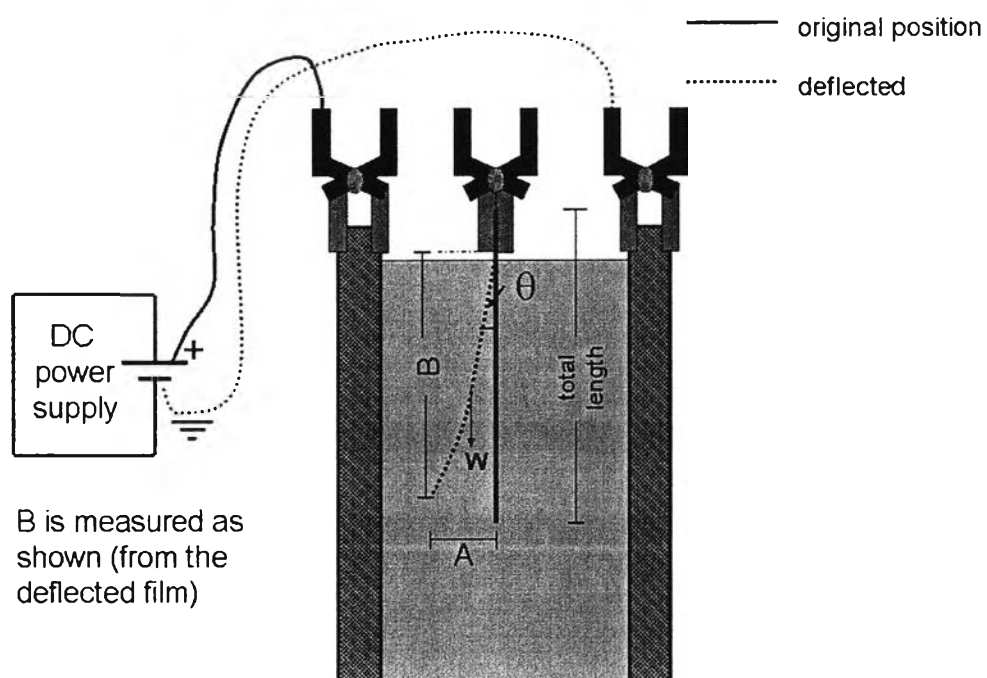


Figure 8.8 Schematic diagram of the apparatus to used observe the dielectrophoretic of PANI/PDMS composite films. The PDMS/PANI films are suspended vertically in a silicon oil bath, with a dc electric field applied horizontally, a deflection of the film occurs from its original position (solid line) to a new position (dotted line).

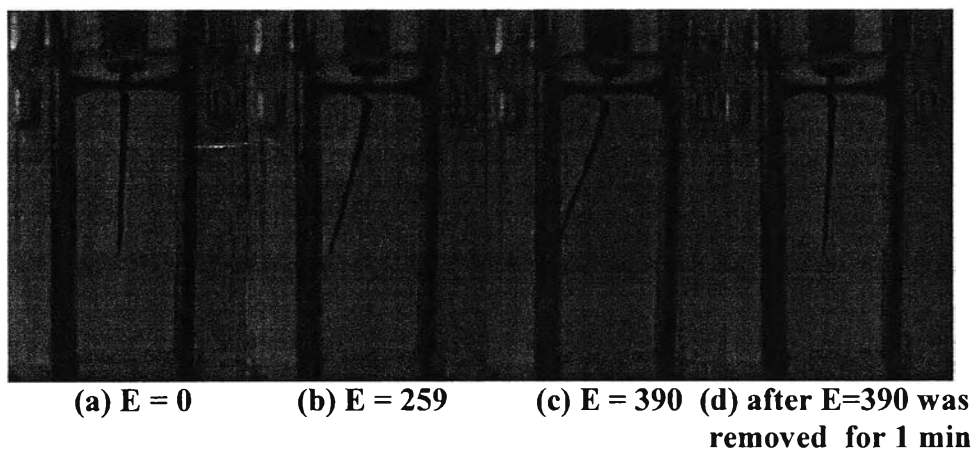


Figure 8.9 Deflection of a 10 vol% PANI/PDMS composite film ($C/M = 0.053$) as a function of electric field strength (V/mm).