

CHAPTER VII
EFFECTS OF FREQUENCY AND AMPLITUDE OF AC ELECTRICAL
FIELD ON THE DIELECTROPHORESIS FORCE OF POLY(P-
PHENYLENEP)/ACRYLIC ELASTOMER

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Abstract

The effects of frequency and amplitude of an AC electric field on the deflection and the dielectrophoresis force of an acrylic elastomer (AR71), styrene copolymers (SAR and SBR), and polymer blends of doped poly(p-phenylene) and acrylic elastomers (AR71) are investigated. The dielectrophoresis forces of the dielectric elastomers and blends were measured and determined by using a vertical cantilever fixture at various frequencies (0.3 to 60 Hz) and at AC electric field strengths of 200, 300, 500, 600, and 800 V_{pp}/mm. In addition, the effects of the thicknesses of the specimens and the particle concentration on the dielectrophoresis force are studied. The doped poly(p-phenylene) particles are embedded in the AR71 with particle concentrations of 1, 10, and 20 %vol. The forces are calculated from the non-linear deflection theory of the cantilever. The dielectrophoresis forces and deflection distance of the dielectric elastomers and blends generally increase with increasing amplitude but slightly decrease with increasing frequency; and they dramatically drop at the cut-off frequency. The cut-off frequencies were 7.84, 1.45, and 0.74 Hz for AR71, SAR, and SBR, respectively, at an E of 800 V_{pp}/mm and a thickness of 0.7 to 0.8 mm. After blending the AR71 with doped PPP, the cut-off frequencies of the 1 %vol, 10 %vol and 20 %vol of doped PPP are 18.51, 15.28, and 10.67 Hz, respectively, at an E of 800 V_{pp}/mm and a thickness of 0.2 to 0.3 mm. The conductive particles, acting as a filler, can improve the electromechanical responses of the materials at high frequency.

Keyword: dielectric elastomers, dielectrophoresis force, frequency, peak to peak amplitude, polymer blends, AC field

Introduction

Electroactive polymers (EAPs) are polymers that can convert electrical energy into mechanical energy [1, 2]. They offer promising and novel characteristics: light weight, high energy density, and high flexibility; they are material candidates for muscle-like actuators [3]. EAPs can also be used in many other applications, such as controllers, pumps, motors, robotic parts, artificial muscles, muscle/insect-like actuators, and MEM or NEM devices [3]. EAPs can be divided into eight types [1]: piezoelectric polymers such as PVDF (polyvinylidene fluoride); dielectric elastomers such as polyurethane or PDMS; electroactive celluloses; liquid crystal elastomers; ionic polymer gels; ionomeric polymer–metal composites (IPMCs); conductive polymers; and carbon nanotubes. Several research groups have attempted to blend two EAPs— such as the silicone elastomer filled with lead magnesium niobate–lead titanate [4], polyanilene-EPDM composite [5], TiO₂ embedded in PDMS gels for actuator applications [6], and the silicone elastomers blends with poly(p-phenylene) [7]— to improve the mechanical properties and processing conditions.

Diaconu *et al.* [8] investigated the % strain responses of a polyurethane elastomer-based polyester. The deformation of dielectric elastomers under applied electric field strength generally comes from two effects. The first effect is the Maxwell stress and the second effect is electrostriction. Maxwell stress is the force that is generated by the attractive force between unlike charges on the top and bottom compliant electrode surfaces under applied electric field [9]. On the other hand, electrostriction is the direct coupling between the electric polarization and the mechanical response of the materials [10]. The ratio of Maxwell stress to electrostriction on the electromechanical response depends on the chemical composition, processing conditions of the sample, and the thermal and mechanical treatment of the materials [8].

Ma *et al.* [11] studied the % strain induced by an AC electric field on acrylic elastomers. The % strain increased with increasing amplitude of the AC field, but decreased with increasing frequency. They concluded that acrylic elastomers were suitable for use in low–frequency applications [11]. Shiga *et al.* [12] investigated the bending of poly(vinyl alcohol)–poly(sodium acrylate) blend films under an AC field.

The films responded under application of the electric field, but did not respond at high frequency [12]. Yun *et al.* [13] studied the deflection of an electroactive cellulose under vertical mode. The deflection distance and the dielectrophoresis force of the electroactive cellulose depended on the thickness of the specimens and the frequency of the AC field.

In our work, we investigate the electromechanical responses of acrylic elastomers (AR71), styrene-acrylic copolymers (SAR), and styrene-butadiene copolymers (SBR) in terms of the deflection distance, angle, and the dielectrophoresis force. We focus on the effects of frequency and peak-to-peak amplitude (V_{pp}) of AC electric fields on the deflection distance and on the dielectrophoresis force at room temperature. In addition, we also study the effect of doped poly(*p*-phenylene) particles on the deflection angle and the dielectrophoresis force of the blends.

Experimental

Materials

A benzene solution (AR grade, Thai Aromatic Co., LTD) was used as the monomer. Aluminium chloride, $AlCl_3$ (AR grade, Riedel-delHean), was used as the oxidant. Cupric chloride, $CuCl_2$ (AR grade, Fluka-Aldrich), was used as the catalyst. The sulphuric acid dopant, H_2SO_4 (AR grade, Lab-Scan), was used as received.

The acrylic elastomer, Nipol AR71 ($T_g = 258$ K) was provided by Nippon Zeon Polymix Advance Co., Ltd. The styrene-butadiene rubber latex (UCAR DL849, $T_g = 312$ K), and the styrene-acrylic-copolymer latex (UCAR DA27, $T_g = 297$ K) were provided by Dow Chemical Co., Ltd. The silicone oil, poly(dimethylsiloxane) 200[®] fluid, was supplied by Dow Corning Corp. The oil had a kinematic viscosity of 100 cSt and was used as the medium in the deflection experiments.

*Synthesis of poly(*p*-phenylene) and preparation of the polymer blend*

In this work, we followed the poly(*p*-phenylene) synthesis procedure of Kovacic [14] using benzene, $AlCl_3$, and $CuCl_2$. The reaction was carried out under

nitrogen in a 3-neck flask equipped with a paddle stirrer. After a dropwise addition of benzene (1 mole) and aluminum chloride (0.5 mole), cupric chloride (0.5 mole) was introduced into the solution. The temperature was raised to 308 to 310 K, and the reaction was allowed to proceed for 3 hours. Then the solution was cooled to 278 K and filtered with a 18 % HCl solution. The obtained poly(p-phenylene) powder was washed with boiling 18 % HCl solutions until the washing solutions were colorless. The poly(p-phenylene) powder was finally washed with hot water until the washings had a pH of 7.0. After drying at 300 K under vacuum for 12 hours, the final obtained product was in the form of a finely divided, light brown solid powder. Great care was taken to avoid contamination from moisture [14]. A suspension of dried poly(p-phenylene) powder in sulphuric acid was prepared in a sealed flask. The mole ratio of the sulphuric acid (N_{acid}) to mole ratio of the PPP monomer (N_{monomer}) was 100:1. The mixture was stirred for 2 hours, at a temperature of 278 K under nitrogen atmosphere. The doped poly(p-phenylene) was filtered out by a funnel. After drying at 300 K under vacuum for 12 hours, the obtained products were dark brown powders whose color depended on the degree of doping.

Preparation of the specimens

All of the elastomer specimens were fabricated through solution casting. The SAR and SBR specimens were formed by water evaporation; the AR71 specimens were dissolved in toluene at 30 % vol/vol. The solutions were cast onto a mold and the solvent was eliminated under a vacuum at 300 K for 72 hours. The blends were prepared by the mechanical blending of poly(p-phenylene) with an acrylic elastomer. We dissolved the acrylic elastomers in toluene and stirred for about 10 hours. Then we added the doped PPP powder and stirred the mixture over night. The dispersion of particles was random. The concentrations of the doped PPP in the AR71 prepared were 1, 10, and 20 %vol. The solution was cast into sheets in a mold and left in a vacuum oven at 300 K for 24 hours to remove bubbles. Each sample was cut into a thin ribbon (initial length \approx 20 mm, width \approx 2.2 mm, and thickness \approx 0.1 to 1.0 mm). The specimens were immersed in the silicone oil 200[®] fluid overnight before testing.

Characterization and testing

The dielectric constants were measured by an LCR meter (HP, model 4284A) connected to a rheometer (Rheometric Scientific, ARES) fitted with a 25 mm parallel plate fixture. The thickness of the specimens was typically 1 mm and the diameter was about 25 mm. Before each measurement, the top and bottom sides of the specimens were coated with a silver adhesive to improve the electrical contact between the specimens and the electrodes. (The dielectric constant at the frequency of 20 Hz will be referred to as the dielectric constant of the materials.)

The particle sizes of the doped PPP were determined by using a particle size analyzer (Malvern Instruments Ltd. Masterizer X Version 2.15). The lenses used in this experiment were 30 mm.

The morphologies of the polymer blends were observed by SEM, Hitachi, model S-4800. The scanning electron micrographs of the blends were obtained by using an acceleration voltage of 3 kV at a magnification of 1500x. The specimens were stacked onto stubs by using sticker carbon papers and were coated with platinum using an ion coating machine (Hitachi, model E-1010) at 120 sec, to enhance the electron conductivity.

The dielectrophoresis forces were determined by measuring the deflection distances of the elastomers in the vertical cantilever fixture under electric field. (The experimental setup is shown in Figure 3a) The specimens were vertically immersed in the silicone oil (viscosity = 100 cSt) between parallel copper electrode plates (40 mm long, 30 mm width, and 1 mm thick). The gap between the electrodes was 10 mm. An AC field was applied with a function generator (Tektonix, model CFG 253) connected to a high-voltage power supply (Trek, model 609E-6) that can deliver an electric field up to 4 kV. The output voltage and frequency from the high-voltage power supply was detected using a voltage meter (Tektonix, model CDM 250) and an oscilloscope (BK Precision, model 2120B), respectively. We used a CCD video camera (SONY Handycam, model HDR-SR1, 4 Mpixel) to record the movement during the experiment. Still pictures were captured from the video and the deflection distances along the x (d) and y axes (l) at the ends of the specimen were determined by using Scion Image software (version 4.0.3). The electric field strength was varied between 0 to 800 V_{pp}/mm at room temperature, 300 ± 1 K. We calculated the

resisting elastic force of the specimens under electric field using the non-linear deflection theory of a cantilever [15, 16], which can be calculated from the standard curve between $\frac{F_e l_0^2}{EI}$ and $\frac{d}{l_0}$ (l_0 = initial length of specimens) [15], where F_e is the elastic force, d is the deflection distance in the horizontal axis, l is the deflection distance in the vertical axis, E is the Young's modulus, and I is the moment of inertia, $\frac{1}{12}t^3w$, where t is the thickness of the film and w is the width of the film.

The dielectrophoresis force can be calculated from the static horizontal force balance, consisting of the elastic force and the corrective gravity force term ($mg\sin\theta$):

$$F_d = F_e + mg \sin \theta , \quad (1)$$

where $g = 9.8 \text{ m.s}^{-2}$, m = the mass of the specimen, and θ is the deflection angle.

Results and Discussion

Dielectric constant of the pure elastomers and the blends

The dielectric constants of AR71, SAR, and SBR, obtained at $T = 300 \text{ K}$ at a frequency of 20 Hz, were 6.33, 3.95, and 2.87, respectively [16]. These dielectric constants decrease slightly with increasing frequency due to the diminishing interfacial polarization. The dependence of the dielectric constant on frequency can be expressed as [17]:

$$\varepsilon' = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + \omega^2 \tau^2} , \quad (2)$$

where ε' is the dielectric constant, ε_∞ is the dielectric constant at infinitely high frequency, ε_s is the dielectric constant at low frequency, ω is frequency, and τ is the relaxation time [17].

The dielectric constants of undoped PPP, doped PPP, and the blends at 1 %vol, 10 %vol and 20 %vol of doped PPP were 7.30, 59.71, 7.17, 10.63, and 25.05, respectively at $f = 20 \text{ Hz}$. The dielectric constants of the polymer blends increased with increasing doped PPP particle concentration (Figure 1). This indicates that the conductive particles can improve the electrical properties of the matrix.

Shiga *et al.* [18] investigated the electrical properties of blends of doped poly(p-phenylene) and silicone rubber. They doped poly(p-phenylene) with CuCl_2 and measured the dielectric constant of the doped PPP. The dielectric constant of the doped PPP, with 0.51 %w/w of CuCl_2 at 1 KHz, was 68.2. Plochanski *et al.* [19] studied the electrical conductivity and the dielectric constant of Poly(p-phenylene) doped with iron (III) chloride. The electrical conductivity and the relative dielectric constant of poly(p-phenylene) increased from 10^{-10} S/cm and 3 to 10^{-3} S/cm and 100, respectively, after doping with 4 %w/w of iron (III) chloride.

Morphology of the pure acrylic elastomer (AR71) and the blends

From our previous work, the average particle diameter of doped poly(p-phenylene) was approximately 46 μm with a standard deviation of 2 μm [20]. The morphology of the pure acrylic elastomer (AR71) and the blends was observed using a scanning electron microscope (SEM, Hitachi, model S-4800). Figure 2a shows the morphology of the pure AR71; they appear to be smooth. Figures 2 b–d—of the polymer blends between AR71 and 1 %vol, 10 %vol, and 20 %vol of doped poly(p-phenylene)—show that particles are moderately dispersed in the AR71 matrix. The particles become more agglomerated with increasing PPP concentration.

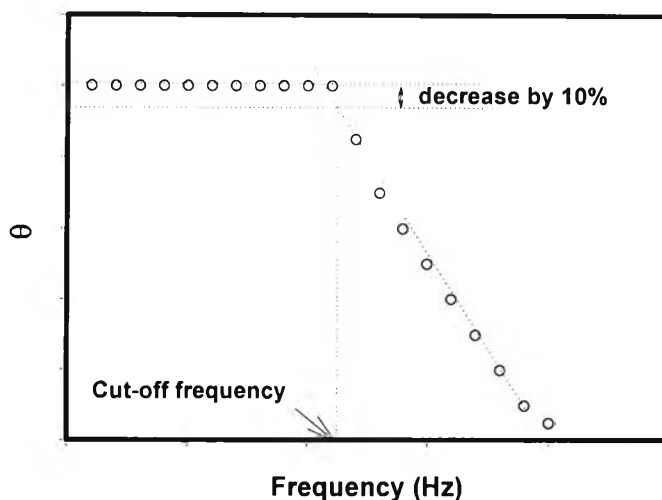
Deflection of the pure dielectric elastomers and the blends under AC field

The deflection angle and the dielectrophoresis force of the three dielectric elastomers (AR71, SAR, and SBR) were investigated under the peak-to-peak amplitudes of 0, 200, 300, 500, 600, and 800 V_{pp}/mm at a temperature of 300 ± 1 K, and a frequency of 0.3 Hz. Initially, all of the specimens were straight in the middle of the testing fixture, without electric field (Figure 3a). After applying an AC electric field, the specimens started to deflect towards the electrode, as shown in Figure 3b. EDX results clarified the deflection in the opposite direction [21]. The acrylic elastomer, (AR71), and styrene-butadiene rubber, (SBR), deflect towards the anode side under applied electric field due to the non-symmetric polarity of the polar groups on the polymer chains [22]. On the other hand, the styrene-acrylic copolymer deflects towards the cathode side. This behavior results from the presence of Cu and Zn metal ions residing within the SAR. The ions can be ionized to become positively charged (Cu^{2+} and Zn^{2+}) under an applied electric field [23, 24].

The electrical yield strengths—the electric field strength required for the materials to start to deflect—of AR71, SAR, and SBR are 200, 600, and 800 V_{pp}/mm , respectively. These data suggest that AR71 requires the lowest electrical energy to respond. Figures 4a–d show the deflection angles and the dielectrophoresis forces of AR71, SAR, and SBR versus amplitude. From these figures, the deflection angles and the dielectrophoresis forces become higher with increasing peak to peak amplitude. At $E = 800 V_{pp}/mm$ and $f = 0.3$ Hz, the AR71 shows the highest deflection angle, at 17.99 degrees, whereas the SBR shows the lowest angle of only 2.42 degree. The dipole moments of the molecules are generated after applying the AC electric field. The functional and/or polar groups on the polymer chains become polarized. As the amplitude of AC electric field strength increases, it leads to a further increase in the internal dipole moments, leading to the increase in the degree of interaction with the electrodes.

Cho *et al.* [24] studied the bending of an electroactive cellulose coated with polypyrrole. The bending distance increased with increasing amplitude of the AC field. Narita *et al.* [25] investigated the bending of soft lead zirconatetitanate (PZT) laminated with thin metal layers (nickel). The bending distance dramatically increased with increasing AC electric field strength (in the unit of peak amplitude, V_p) from 0.1 MV_p/mm to 0.3 MV_p/mm . The tip deflection was due to the larger increase in the domain wall motion of PZT under the influence of the AC electric field [25].

The effects of frequencies of AC electric field on the deflection angle and dielectrophoresis force were investigated here between 0.3 Hz and 60 Hz at a temperature of 300 ± 1 K. At the low frequency, the deflection angles and the dielectrophoresis force are nearly independent of frequency (Figures 4a–d). With increasing frequency, the deflection angles and the dielectrophoresis force become more frequency-dependent. The cut-off frequency is defined as the frequency at which the response of the material starts to decrease by 10 % from the plateau value (The estimated scheme is shown in Scheme I).



Scheme I Determination of the cut-off frequency

The cut-off frequencies of the AR71, SAR, and SBR, at an amplitude of 800 V_{pp}/mm , and a thickness of 0.7 to 0.8 mm, are 7.84, 1.45, and 0.74, respectively. These data suggest that AR71 has a better frequency response than those of SAR and SBR (under the same thickness). From Table 1, the cut-off frequencies of the AR71 and SAR slightly increase with increasing peak-to-peak amplitude (V_{pp}) of AC electric field. Ma *et al.* [11] investigated the %strain changes by the AC electric field (in terms of peak amplitude, V_p) of the acrylic elastomer VHB4910. Its %strain of the acrylic elastomer (VHB4910) dramatically decreased with an increasing of the frequency of AC field from 1 Hz to 25 Hz. Yun *et al.* [13] reported that the resonance frequency of electroactive celluloses slightly increased with increasing peak amplitude (V_p) of AC field when the thickness of the films were 30 and 40 μm .

The effect of thickness on the deflection angle and dielectrophoresis force is shown in Figures 5a and 5b. The deflection angle and dielectrophoresis forces of our materials were measured at 800 V_{pp}/mm with various thicknesses between 0.11 and 0.93 mm. Initially, the deflection angle and the force increase with increasing thickness and attain the optimum values at $t = 0.25$ mm and then decrease. The cut-off frequency, increases with thickness and attains its maximum value at $t = 0.52$ mm.

Yun *et al.* [13] found that as the thickness of electroactive celluloses increased, the maximum deflection distances varied accordingly. The maximum the

deflection distance and the maximum dielectrophoresis force of electroactive cellulose were 4.2 mm and 12.66 mN, respectively, at a thickness of 30 μm [13]. The resonance frequency—the frequency which gives the highest deflection distance—of electroactive cellulose increases with increasing thickness, from 20 μm to 40 μm .

The effect of particle concentration on the deflection angle and the dielectrophoresis force of polymer blends between doped poly(p-phenylene) and acrylic elastomers (AR71) is shown in Figures 6a, 6b, and Table 3. The deflection angle and dielectrophoresis forces increase with increasing particle concentration from 0 to 10 %vol. From Figures 6a and 6b, a 10 %vol of AR71:doped PPP shows the highest response under electric field, relative to others. As more particles are added to the matrix, the distances between the particles become smaller, and stronger interparticle interactions result. However, the deflection angle and force decrease at 20 %vol because the stiffness and rigidity of the polymer blend provide a resistance against the deflection. From Figures 6a and 6b, the cut-off frequencies of the polymer blends are higher than those pure acrylic elastomer. Adding the conductive particles, doped poly(p-phenylene), into the acrylic matrices can enhance the mechanical responses of the materials at high frequency.

Thuau et al. [26] studied the dielectrophoresis effect of carbon nanotubes embedded in a polyimide matrix. They reported that the presence of the conductive particles improved the resultant dielectrophoresis force on the polymer matrix [26]. Gharavi *et al.* [27] investigated the stress responses of organically modified montmorillonite (OMMT) nanoclay–silicone elastomer composites. They showed that stress responses of the composites were always higher than that of pure silicone rubber [27].

Comparison with other types of electroactive materials

The electromechanical responses of the dielectric elastomers and blends were compared with other types of electroactive materials (Table 4). The blends between 10 %vol of doped PPP and acrylic elastomer, AR71, provide the highest dielectrophoresis force when compared with other types of electroactive materials. For the deflection distance, the electroactive cellophane coated with polypyrrole gives the highest values whereas PDMS [28, 29] and PZT [25] possess the lowest. In term of the cut-off frequency, PZT (lead zirconate titanate) has the ability to respond

at the highest frequency (120 Hz) [25] whereas our dielectric elastomers (AR71, SAR, and SBR) and the blends have a limited ability to respond at high frequency ($f > 20$ Hz). However the blends with 10 %vol of doped PPP provide a higher cut-off frequency than all of the pure dielectric elastomers (AR71, SAR, PDMS, and SBR) and the electroactive cellulose.

The main disadvantage of the dielectric elastomers is the high driving voltage required for actuation. From Table 4, we can see that the electroactive cellulose [24, 30, 31] and PZT [25] can respond under low electric field strength whereas the dielectric elastomers have this limitation as a weak point. After blending with the high dielectric particles, the deflection distance and dielectrophoresis force are improved (Table 4).

Conclusion

In our work, the deflection angles and the dielectrophoresis force of AR71, SAR, and SBR were investigated by examining the effects of the amplitude of AC field strength, the frequency, the thickness of the specimens, and the conductive particle concentration. The deflection angle, the force, and the cut-off frequency of the elastomers increase with increasing peak-to-peak amplitude of the AC field. But the deflection angle and the force decrease with increasing frequency. The optimum thickness of the AR71 is 0.25 mm, which gives the highest deflection and the dielectrophoresis force at $E = 800$ V_{pp}/mm. The deflection angle and the force increase beyond a concentration of 10 %vol PPP at $E = 800$ V_{pp}/mm. However, both decrease at 20 %vol because of the stiffness and rigidity of the polymer blends. The cut-off frequencies of all of the polymer blends are higher than that of the pure AR71. The conductive particles act as filler and can improve the electromechanical responses of the materials at high frequency.

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Table 1 Electromechanical responses of all of the elastomers at various AC electric field strengths

Elastomers	Electric field strength (V_{pp}/mm)	Cut-off frequency (Hz)	Maximum deflection distance (mm)	Maximum deflection angle ($^{\circ}$)	Maximum F_d (mN)
AR71	200	3.86	0.20	1.122	0.011
AR71	300	5.18	0.32	1.786	0.021
AR71	500	5.47	0.43	2.235	0.024
AR71	600	5.52	1.15	5.283	0.040
AR71	800	7.84	3.88	17.99	0.185
SAR	600	1.11	0.63	2.96	0.027
SAR	800	1.45	1.38	6.29	0.071
SBR	800	0.74	0.50	2.42	0.008

Table 2 Electromechanical responses of AR71 at various thicknesses

Elastomer	Electric field strength (V_{pp}/mm)	Thickness (mm)	Cut-off frequency (Hz)	Maximum deflection distance (mm)	Maximum deflection angle ($^{\circ}$)	Maximum F_d (mN)
AR71	800	0.11	0.97	4.11	21.71	0.103
AR71	800	0.25	0.99	4.27	21.96	0.207
AR71	800	0.52	8.65	3.95	19.14	0.177
AR71	800	0.79	7.84	3.88	17.99	0.185
AR71	800	0.93	4.13	1.41	7.59	0.074

Table 3 Electromechanical responses of AR71:doped PPP at various concentrations

Elastomers	Electric field strength (V_{pp}/mm)	Thickness (mm)	Cut-off frequency (Hz)	Maximum deflection distance (mm)	Maximum deflection angle ($^{\circ}$)	Maximum F_d (mN)
Pure AR71	800	0.25	0.99	4.27	21.96	0.207
AR71:doped PPP 1%	800	0.31	18.51	4.28	22.27	0.346
AR71:doped PPP 10%	800	0.30	15.28	4.26	23.95	0.419
AR71:doped PPP 20%	800	0.27	10.67	2.07	10.54	0.229

Table 4 Electromechanical responses of various electroactive materials

Materials	Test Fixture	Maximum Deflection Distance (mm)	Dielectrophoresis Force (mN)	Cut-off Frequency (Hz)	%Strain (%)	Voltage (V/mm)	References
Acrylic Elastomers (AR71) $t = 0.25$ mm	Vertically Cantilever	4.27	0.207	0.99	N/A	800 (V_{pp})	-
Acrylic Elastomers (AR71) $t = 0.79$ mm	Vertically Cantilever	3.88	0.185	7.84	N/A	800 (V_{pp})	-
Styrene-Acrylic Copolymers (SAR)	Vertically Cantilever	1.38	0.071	1.45	N/A	800 (V_{pp})	-
Styrene Butadiene Rubber	Vertically Cantilever	0.50	0.008	0.47	N/A	800 (V_{pp})	-
AR71:doped PPP 1%	Vertically Cantilever	4.28	0.346	18.51	N/A	800 (V_{pp})	-
AR71:doped PPP 10%	Vertically Cantilever	4.26	0.419	15.28	N/A	800 (V_{pp})	-
Lead Zirconate Titanate (PZT)	Horizontally Cantilever	0.38	N/A	120	N/A	3.7 (V_D)	Narita et al. [24]
Silicone Film (HSII)	Vertically Cantilever	N/A	N/A	~6.0	1.5	2,000 (V_D)	Yang et al. [27]
Polydimethyl siloxane (PDMS)	Horizontally Cantilever	0.001	N/A	N/A	N/A	20 (V_{pp})	Tevaa et al. [29]
Electroactive Cellulose (CA-10) under 70% Humidity	Vertically Cantilever	1.8	0.094	~10.0	N/A	7 (V_D)	Kim et al. [30, 31]
Electroactive Cellophane coated with Polypyrrole	Vertically Cantilever	~9.0	N/A	3.7	N/A	4 (V_D)	Cho et al. [23]
Acrylic Elastomers	Compressive Film	N/A	N/A	~1.0	~11.0	40,000 (V_D)	Ma et al. [11]

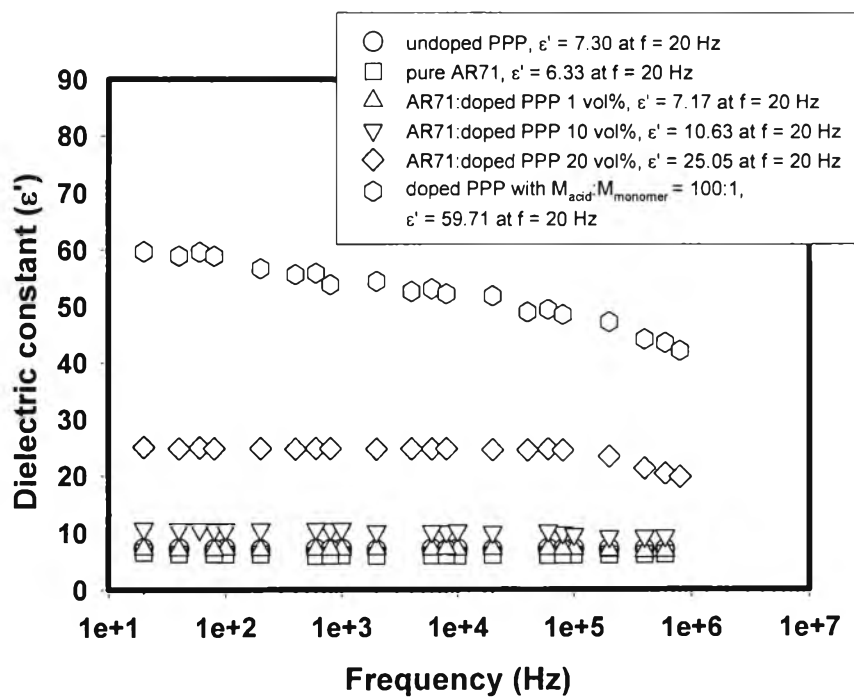


Figure 1 Dielectric constant of undoped PPP, doped PPP, pure acrylic elastomer (AR71), and blends.

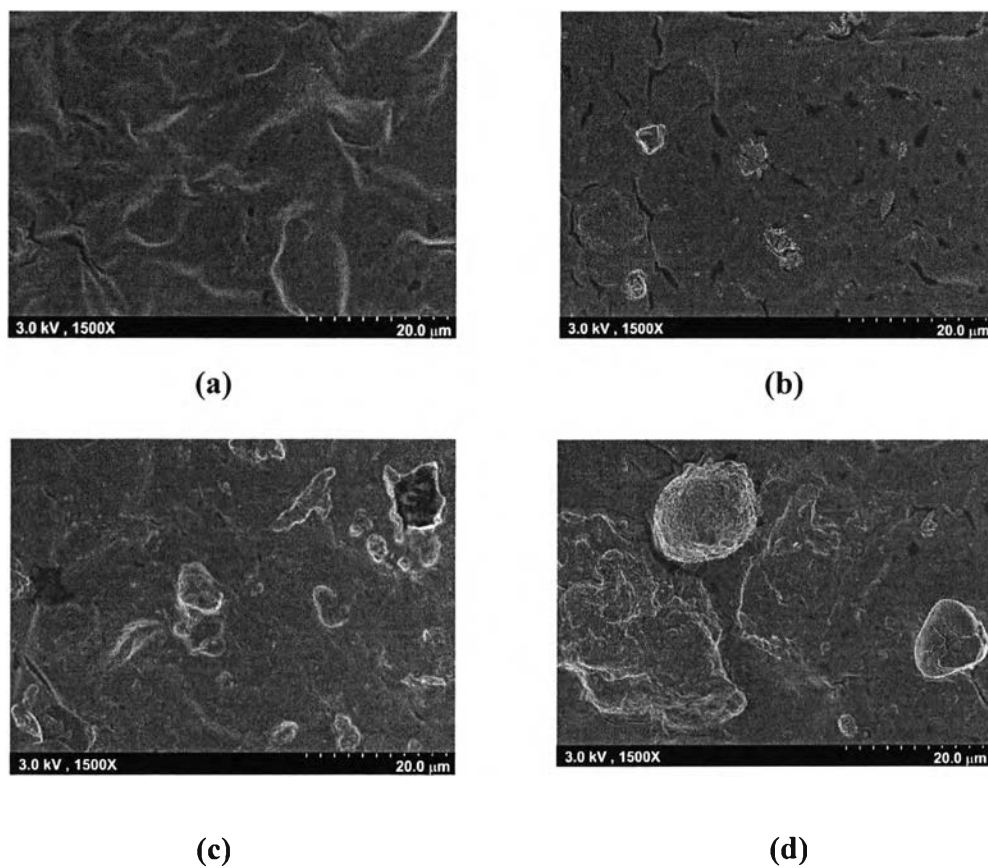


Figure 2 SEM images of pure AR71 and blends at a magnification of 1500x, 20 kV: a) pure AR71; b) AR71:doped PPP at 1 %vol; c) AR71:doped PPP at 10 %vol; and d) AR71:doped PPP at 20 %vol.

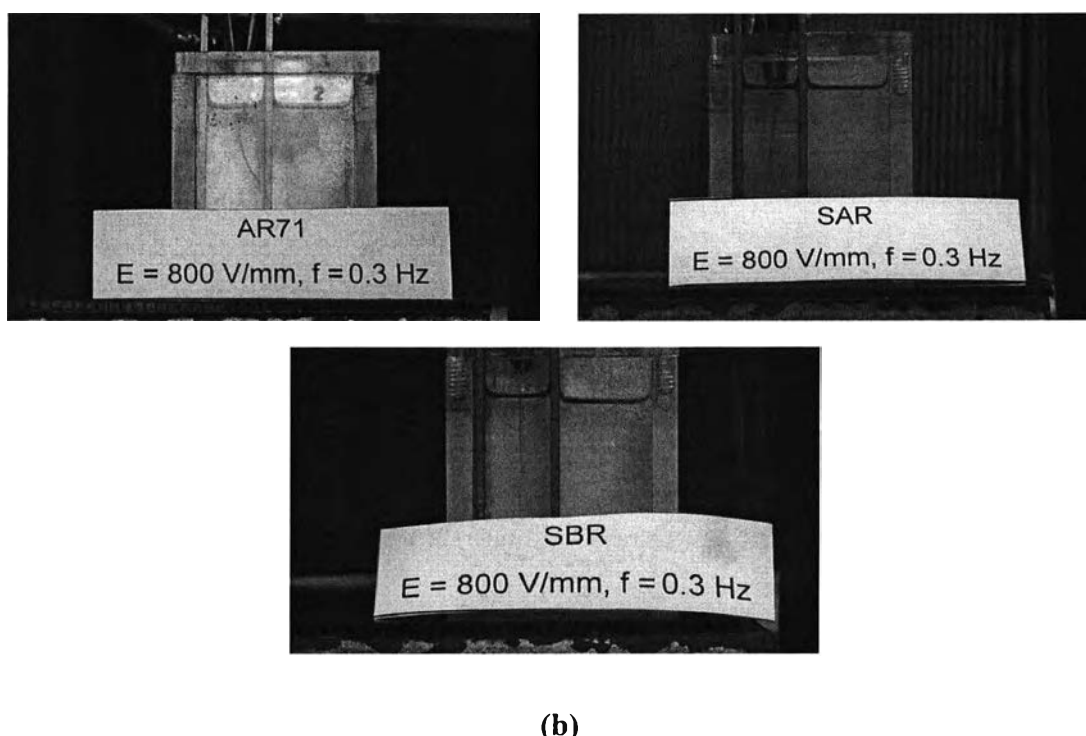
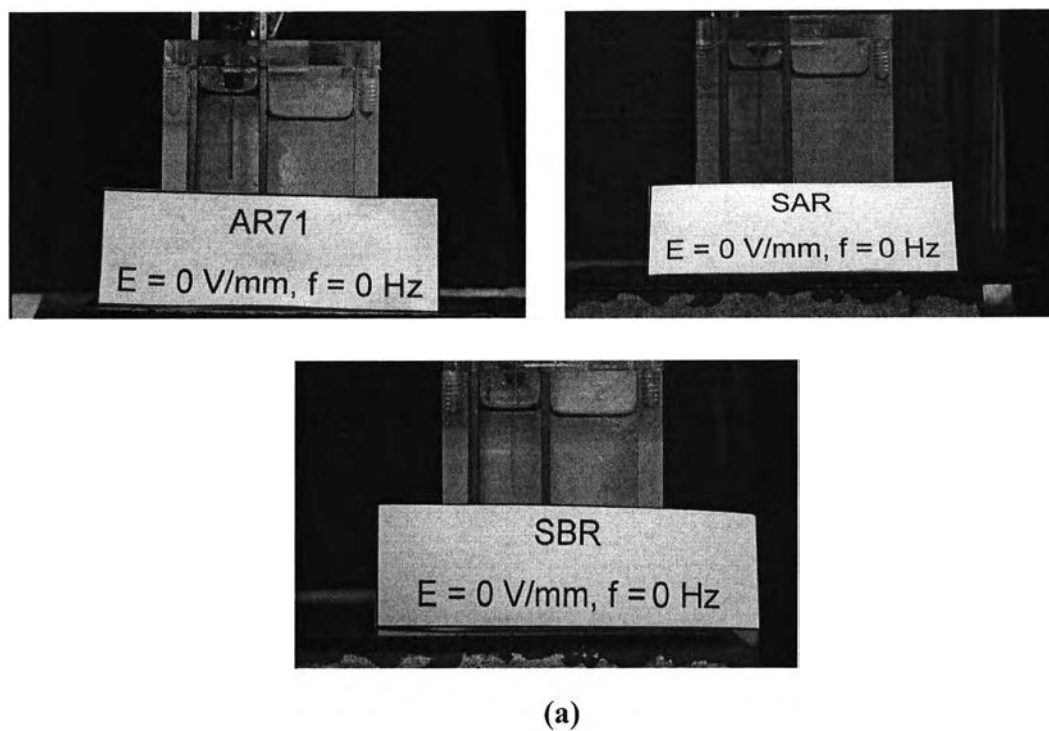
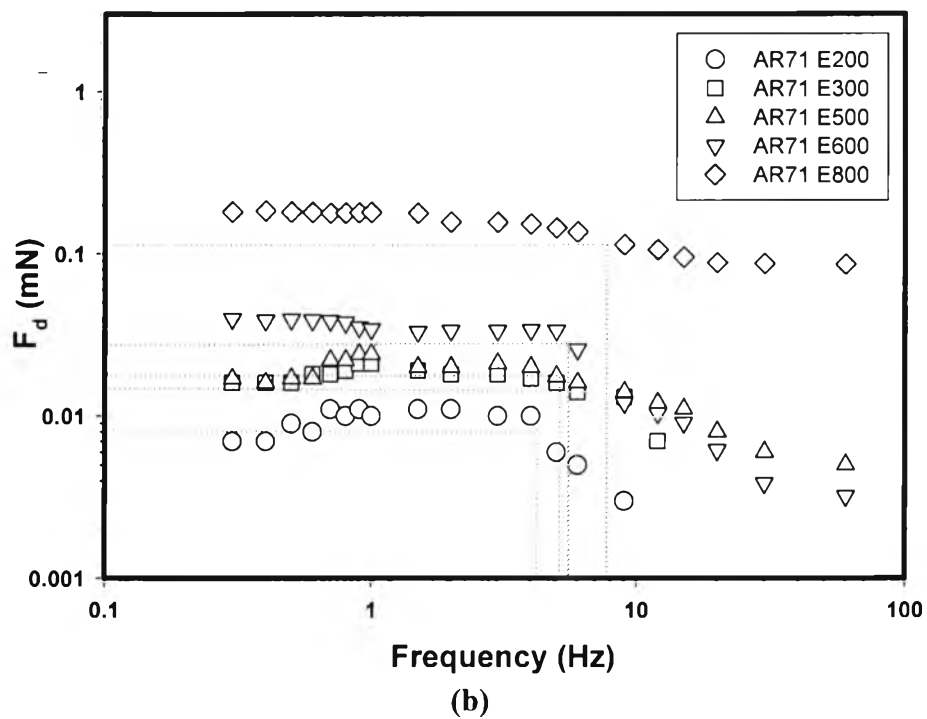
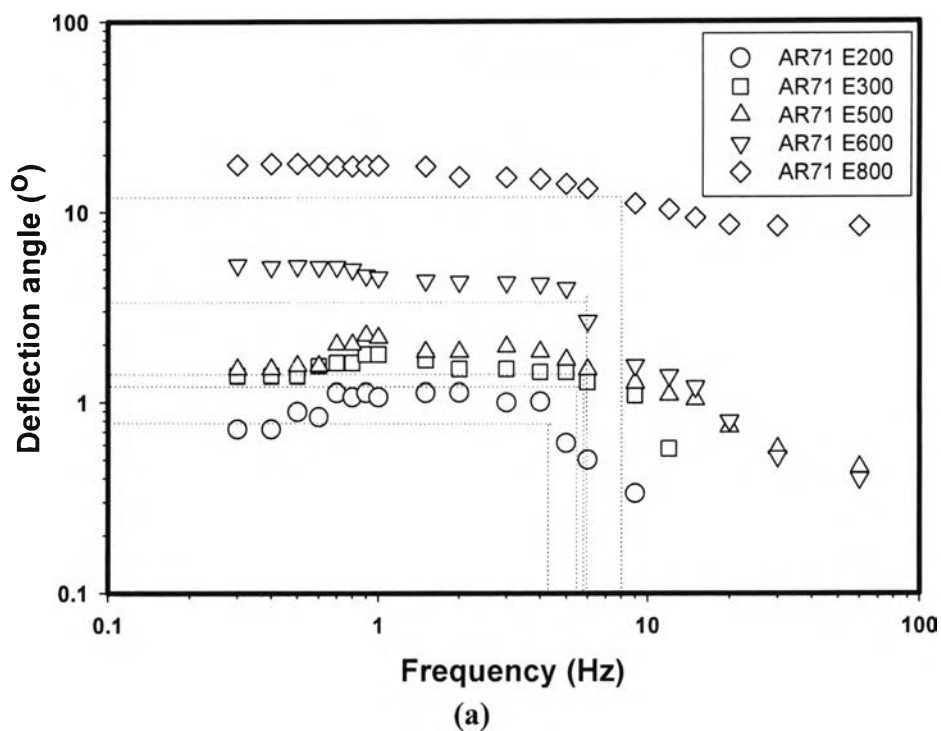
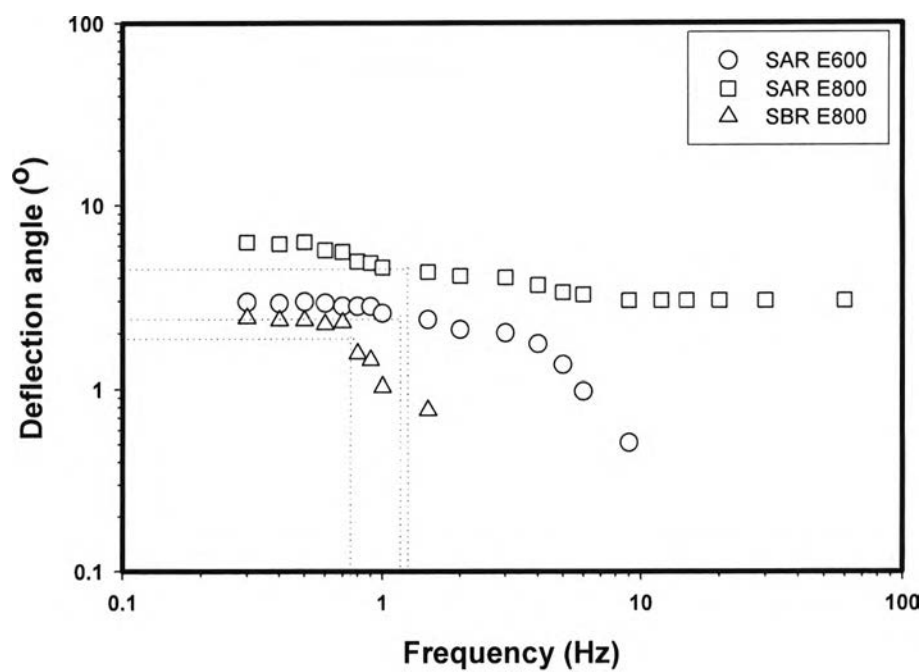
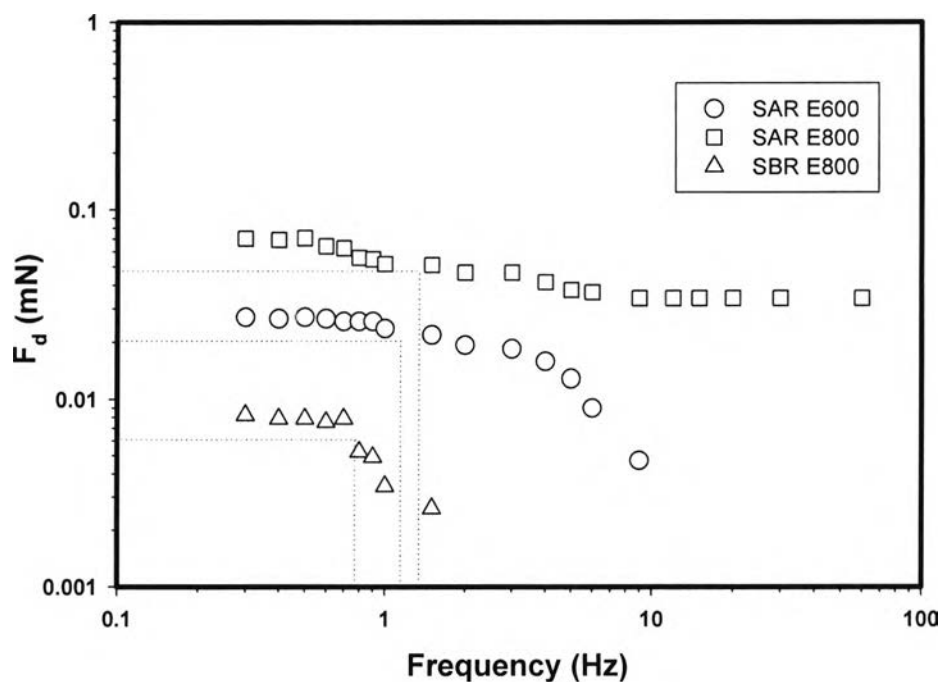


Figure 3 Deflection of the dielectric elastomers and blends at various electric field strengths, frequency = 0.3 Hz, temperature = $300 \pm 1 \text{ K}$: a) without AC field; and b) at an electric field strength of $800 \text{ V}_{pp}/\text{mm}$, at a frequency of 0.3 Hz.



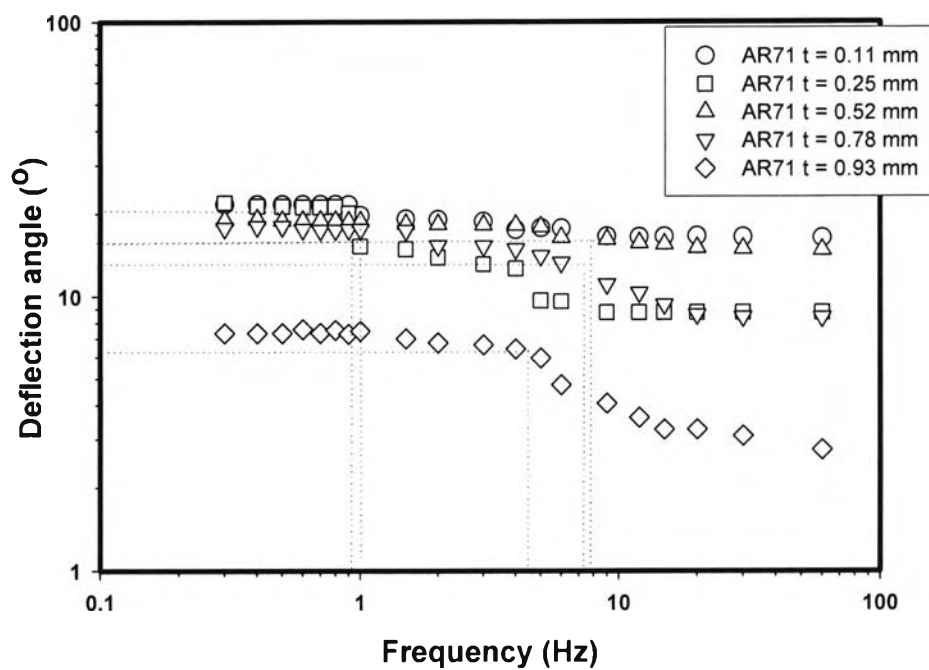


(c)

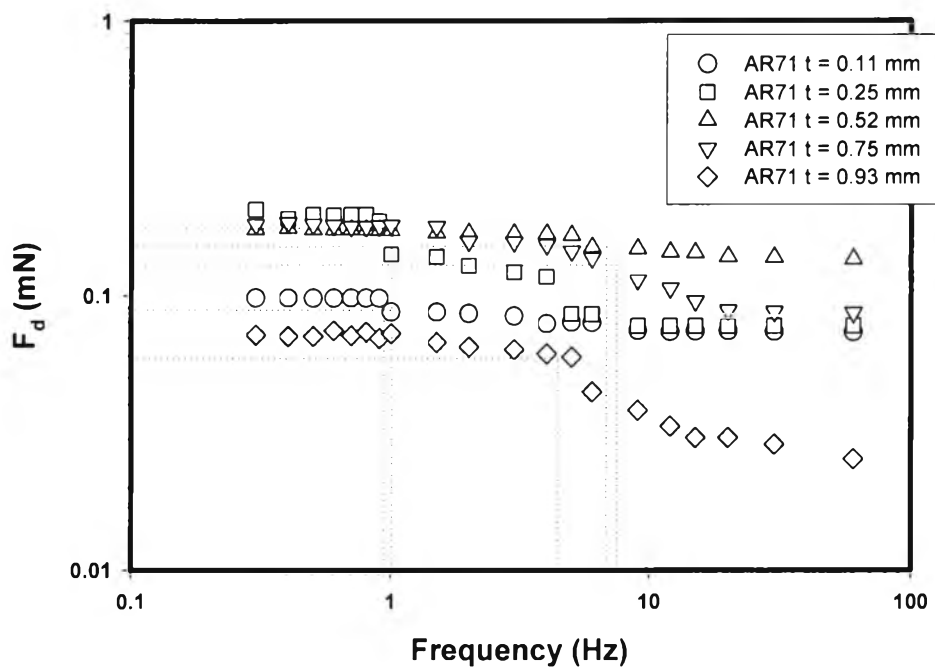


(d)

Figure 4 Electromechanical responses of the elastomers at various frequencies under various AC electric field strengths: (a) deflection angles of the AR71; (b) dielectrophoresis forces (F_d) of the AR71; (c) deflection angles of the SAR and SBR; and (d) dielectrophoresis forces (F_d) of the SAR and SBR.

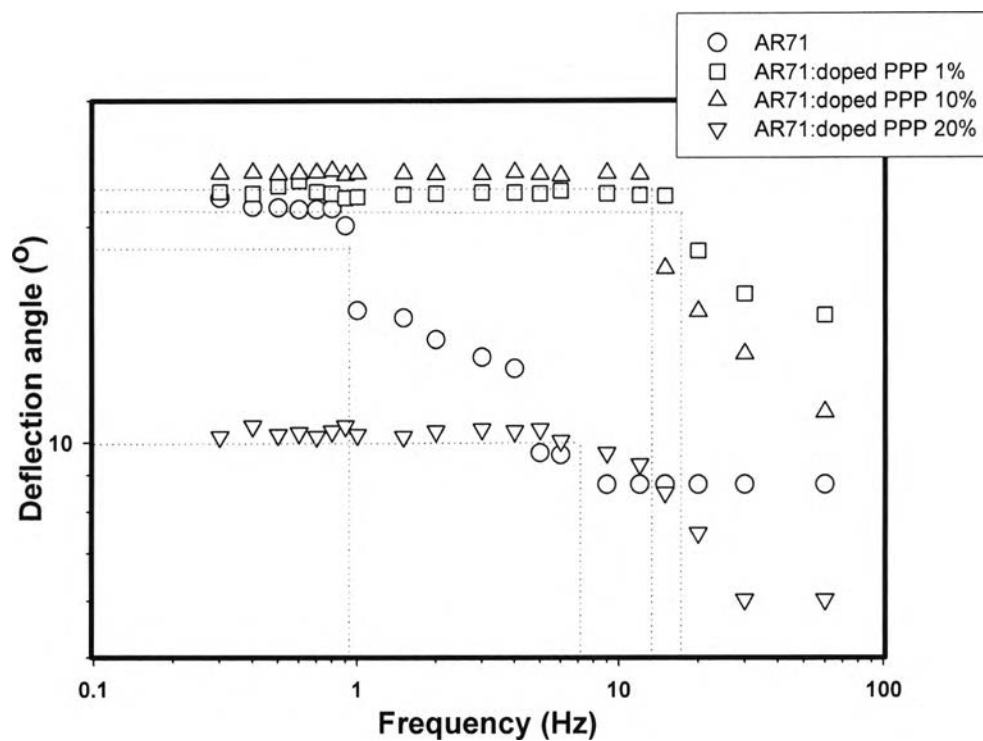


(a)

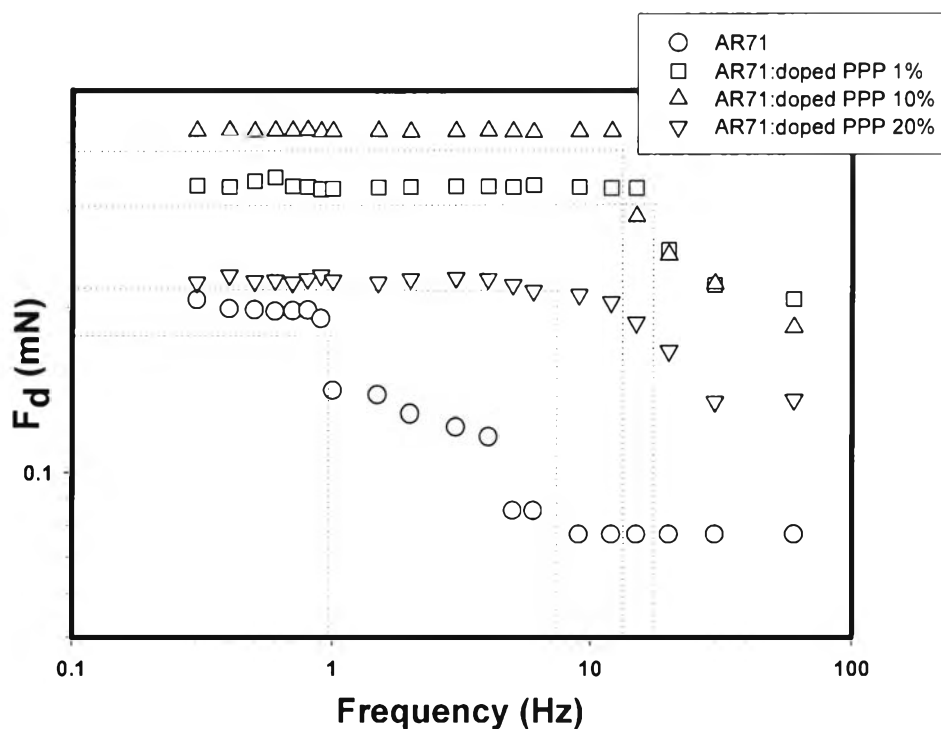


(b)

Figure 5 Electromechanical responses of the AR71 at various frequencies and thicknesses under AC field $E = 800 \text{ V}_{pp}/\text{mm}$: (a) deflection angles; and (b) dielectrophoresis forces (F_d).



(a)



(b)

Figure 6 Electromechanical responses of the AR71:doped PPP (mole acid:mole PPP monomer ratio of 100:1) at various poly(p-phenylene) concentrations under AC field $E = 800 \text{ V}_{pp}/\text{mm}$.