

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

First, the electromechanical properties of pure gelatin and nanowire Ppy/gelatin hydrogels were investigated as functions of electric field strength and operating temperature. In the pure gelatin hydrogel and nanowire Ppy/gelatin hydrogels 0.01, 0.1, 0.5, and 1 vol%., the storage modulus (G'), the storage modulus response ($\Delta G'$) and the storage modulus sensitivity ($\Delta G'/G'_o$) increased monotonically with increasing electric field strength up to 800 V/mm. The maximum storage modulus sensitivity was 104 % for the nanowire Ppy 0.1 vol% / gelatin hydrogel at an electric field strength of 800 V/mm. The mechanism for the storage modulus response was the interaction between electrically polarized nanowire Ppy which induced an electrostatic interaction and the effect of particles acting as fillers. Under the presence of nanowire Ppy, G' and $\Delta G'$ at any temperatures investigated were higher than those of the pure gelatin hydrogel since the nanowire Ppy acted as a filler and created the wire-to-wire dipole interaction under the electric field. For the deflection measurement, the nanowire Ppy 1vol%/gelatin hydrogel possessed the lowest deflection response relative to others due to its initially higher rigidity or its higher G'_o value. However, the nanowire Ppy 0.1 vol%/gelatin hydrogel was shown overall here to be more electroactive than the pure gelatin hydrogel.

Next, the stress relaxation behavior was investigated as an important property for electroactive materials. The relaxations of uncrosslinked and crosslinked gelatin hydrogels were investigated under the effects of the degree of crosslinking and electric field strength. The characteristic relaxation time can be estimated by three methods; KWW; the dynamic crossover; and the relaxation time distribution spectrum $H(\tau)$. For the uncrosslinked, 3 %v/v crosslinked and 7 %v/v crosslinked gelatin hydrogels, the relaxation times decreased with increasing degrees of crosslinking and the applied electric field strengths. This was due to the increase in the molecular connectivity that promoted the capability of the stress relaxation process. The stress relaxation process of the uncrosslinked and crosslinked gelatin

hydrogels showed two relaxation time modes under an applied electric field: fast relaxation mode and slow relaxation mode. The experimental shift factors ($a_{E,exp}$) of the uncrosslinked, 3 %v/v crosslinked, and 7 %v/v crosslinked gelatin hydrogels decreased with increasing electric field strength. The $a_{E,exp}$ characteristic is analogous to the time-temperature superposition. Thus, the existence of the time-electric field superposition was demonstrated here. Furthermore, $a_{E,exp}$ can also be used on the shifting of $G'(\omega)$ - $G''(\omega)$ - $G(t)$ - $H(\tau)$ functions. Effective relaxation times from stress relaxation experiment were used to determine the calculated shift factor, $a_{E,cal}$. The correlation between $a_{E,exp}$ and $a_{E,cal}$ was found to be dependent of the material constant but independent of the applied electric field.

Then, MWNT/gelatin hydrogel composites were studied to enhance the electromechanical properties of the materials. They were investigated under the effects of multi-walled carbon nanotube (MWNT) aspect ratio, electric field, strength and temperature. The highest aspect ratio of MWNT provided the composites with the highest dynamic moduli under electric field due to the stronger interfacial force between the nanotube and the matrix, leading the greater induced dipole moment between particle-matrix interactions. The maximum $\Delta G'$ and $\Delta G'/G_0$ were 2.34×10^5 Pa and 1.25, respectively, for the 0.1 vol% MWNT/gelatin hydrogel composite. For the effect of temperature, both G' and $\Delta G'$ exhibited three behaviors between 30 and 90 °C. From the deflection measurement, the deflection distance and the dielectrophoresis force (F_d) of the pure gelatin and 0.1 vol% and 1 vol% MWNT/gelatin hydrogel composites increased with increasing electric field strength. The 0.1 vol% MWNT/gelatin hydrogel composite exhibited the greatest deflection response; whereas the 1 vol% MWNT/gelatin hydrogel composite showed the lowest deflection distance and F_d due to the particle steric hindrance.

However, graphene can be a substitute of MWNT since it exhibits greater electrical conductivity, higher tensile strength, less defect in structure, and inexpensive when compared with MWNT. Therefore, graphene/gelatin hydrogel composites were studied toward improving the electromechanical properties. The electromechanical properties were investigated under the effects of graphene surface areas, electric field strength and temperature. The highest surface area of graphene (MG; grade M) in the gelatin hydrogel composites provided the highest dynamic

modulus (G') under applied electric field. The graphene (MG)/gelatin hydrogel composites of 0.01, 0.1, 0.5, 1 vol% and the pure gelatin hydrogel exhibited very high storage modulus sensitivity ($\Delta G'/G'_0$) values of 2.53, 3.52, 1.97, 0.99 and 0.44, respectively, at 800 V/mm. The maximum $\Delta G'$ and $\Delta G'/G'_0$ were 1.25×10^6 Pa and 3.52, respectively, for the 0.1 vol% graphene/gelatin hydrogel composite. For the influence of temperature, both G' and $\Delta G'$ showed three regime behaviors in the temperature range of 30–90 °C. Lastly, the deflection distance (d) and the dielectrophoresis force (F_d) of the pure gelatin, 0.1 vol%, and 1 vol% graphene/gelatin hydrogel composites increased monotonically with increasing electric field strength. The 0.1 vol% graphene/gelatin hydrogel composite delivered the greatest d and F_d suggesting that it was the most suitable candidate for actuator applications.

7.2 Recommendations

There are several possible studies on the electromechanical properties of composites for examples; modifying the functional group of the graphene; and gelatin film with plasticizers

The good blending of hydrogel composites can help distribute generated dipole moments between nanofillers and matrix. In this work, the dispersing agent was used to enhance distribution of nanofillers; however, the dispersing agent cannot be used in excess quantities since it can react with the functional groups in gelatin molecules, leading to gelatin gums. The modification of graphene is an alternative way. Graphene can be oxidized to the graphene oxide in which it exhibits more compatibility with the hydrophilic gelatin chain.

Although hydrogel is very promising material for actuator, it cannot be used in the long period due to the water evaporation. In the long term performance, gelatin films are more suitable and develop to bio-actuator by using other plasticizers for enhance elasticity of materials.