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Electric field induced stress moduli in polythiophene/polyisoprene elastomer blends

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Abstract

Electrorheological properties of polyisoprene and polythiophene/polyisoprene blends were investigated for electroactive actuator applications. Experiments were carried out under the oscillatory shear mode and with an applied electric field strength varying from 0 to 2 kV/mm. The dynamic moduli, G' and G'', of the pure polyisoprene were measured in terms of the crosslinking ratio and electric field strength. In the absence of an electric field, the storage modulus (G'') increased but the loss loss modulus (G'') decreased with increasing crosslinking ratio. In the uncrosslinked polyisoprene fluid, the storage modulus (G') exhibited no change in value with increasing electric field strength. For polyisoprene with crosslinking ratios of 2, 3, 5, and 7, the storage modulus sensitivity increased with electric field strength and attained maximum values of 10%, 60%, 25%, and 30%, respectively, at an electric field strength of 2 kV/mm. The dynamic moduli, G' and G'', of blends of polythiophene with undoped particle concentrations of 5%, 10%, 20%, and 30% vol% were generally higher than those of crosslinked polyisoprene. The storage modulus sensitivity of these blends increased with electric field strength and attained maximum values of 50%, 35%, 110% ,and 45%, respectively, at an electric field strength of 2 kV/min.

Keywords: Electrorheological properties; Polyisoprene; Polythiophene; Dynamic moduli

1. Introduction

The exchange of electrical energy to mechanical energy has been of scientific and technological interests for many decades. Electromechanical energy conversion is required in many applications such as muscle/insect-like actuators and robotic characteristics [1]. Electroactive polymers (EAPs) offer promising and novel characters such as lightweight, high energy density and high flexibility, and they are material candidates for muscle-like actuators. Dielectric elastomers belong to a type of electric-field-activated electroactive polymers that are capable of producing large strains, fast response, and

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high efficiency [2]. Polyisoprene or natural rubber is one type of dielectric material which has many useful characteristics: inexpensive due to its natural source, flexible polymer, low swelling in water, high tensile strength, good resilience, high hot tensile, and well behaved hysteresis. These characteristics are desirable properties required to induce large actuation strain when subjecting to an electric field.

Recently, the insertion of a conductive polymer into a dielectric elastomer forming a blend has been of keen interest. Conductive polymers can offer a variety of benefits to the host elastomer: variable conductivity, better thermal stability, and mechanical properties [3]. Examples are a polyanilene-polyisoprene blend for a biosensor application [4], a polyanilene-EPDM blend [5], and TiO_2 embedded in PDMS gels for actuator applications [6].

In our work, we are interested in developing and testing polythiophene/polyisoprene elastomer blends as a substitute for artificial muscles. The mechanical properties, viscoelastic properties and electrical properties will be investigated in terms of degree of crosslinking ratio, polythiophene particle concentration, and electric field strength.

2. The electrorheological effect

For a dielectric elastomer, a simplified description of the ER effect in solid-like matrices is introduced and summarized here. The nature of the ER effect in polymer gels or elastomers can be explained using the one point dipole model. Polarization in the point dipole model occurs not at the surface of the particle but within it. If dipoles form within particles, an interaction between dipoles occurs and becomes stronger as the dipoles come close to each other. When the particles make contact with each other along the applied electric field, the interaction reaches a maximum. A balance between the electrostatic interaction and the elastic modulus of the solid matrix is important for the ER effect to transpire. If the elastic modulus of the solid matrix is larger than the sum of the interaction between particles, the ER effect may not be observed macroscopically. Therefore, the matrix should be a soft material such as gels or elastomers to produce a significant ER response [7].

We may discuss theoretically the influence of microscopic interaction between polarized particles on the macroscopic mechanical properties of the polymer blends, in particular, the elastic storage modulus. Let us consider a hard sphere in a continuous matrix under an electric field. When the relative dielectric constant of the particle (ε_p) is larger than that of the matrix (ε_m), a point dipole in the particle can be generated by application of an electric field. According to the classical theory [7], the point dipole moment is given by:

$$\mu = 4\pi r^3 \varepsilon_0 \varepsilon_m \kappa E \quad (1)$$

$$\text{where} \quad \kappa = (\varepsilon_p - \varepsilon_m)/(\varepsilon_p + 2\varepsilon_m) \quad (2)$$

Eq. (1) is an expression obtained formally for the volume polarizability of a particle, where r is the radius of the particle, ε_0 is the permittivity in vacuum ($=8.854 \times 10^{-12}$ F/m), and E is the applied electric field strength.

When two particles are aligned along the applied electric field and are in contact with each other, the dipole–dipole interaction (F) between two dipole particles is given by the following equation [7]:

$$F = (3/2)\pi r^2 \varepsilon_0 \varepsilon_m \kappa^2 E^2 \quad (3)$$

In a cubical gel, there are many straight migration paths of dispersed particles, which remain parallel to the direction of the applied field. The cube gel is deformed by a small shear strain in a direction perpendicular to the applied field. We may assume that electrostatic interactions between the dispersed particles in a path are based only upon the interaction between two adjacent particles and the interaction between paths of particles is negligible. Macroscopic mechanical properties such as storage and loss moduli can be estimated by multiplying the electrostatic force between adjacent particles at a short range in the path, therefore, an increase in elastic modulus due to an applied electric field ΔG can be calculated as follows [7]:

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

where ΔG is the change in the storage modulus, C is the volume fraction of particles, ε_m is the relative dielectric constant of matrix, and E is the intensity of the applied field. This states that ΔG is proportional to C, ε_m, and E^2. When these factors reach maximum values, ΔG is expected to become saturated.

3. Experimental

3.1. Materials and synthesis of poly(3-thiopheneacetic acid) (Pth)

3-Thiopheneacetic acid, 3TAA (AR grade, Fluka), was used as the monomer. Anhydrous ferric chloride, $FeCl_3$ (AR grade, Riedel-delHean), was