

ELECTRORHEOLOGY AND CREEP-RECOVERY BEHAVIOR OF CONDUCTING POLYTHIOPHENE/POLY(OXYMETHYLENE)-BLEND SUSPENSIONS*

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Abstract Electrorheological properties and creep-recovery behavior of polythiophene/polyoxymethylene-blend having PT(50%)/POM(50%) composition were investigated. Particle size, conductivity and dielectric values were measured to be 24.77 μm , $3.85 \times 10^{-5} \text{ S}\cdot\text{m}^{-1}$ and 26.75, respectively. Sedimentation ratio was measured to be 64% at the end of 16 days. The effects of dispersed particle volume fraction, external electric field strength, shear rate, frequency and temperature on ER properties and storage modulus of PT/POM-blend/silicone oil (SO) suspensions were examined. Enhancement were observed in the electric field viscosities of the suspensions and thus they were classified as a smart material. Shear thinning non-Newtonian viscoelastic behavior was determined for PT/POM-blend/SO system. Further, time-dependent deformation was examined by creep-recovery tests and recoverable viscoelastic deformation established.

Keywords: Conducting polythiophene/poly(oxymethylene) Blends; Electrorheological fluids; Creep-recovery behavior.

INTRODUCTION

In recent years, the manufacturing of blends became very important to obtain new materials by mixing existing well-known polymers^[1]. Blending has become the least expensive and most various way of achieving materials with new desirable properties. Moreover, these mixtures lead to prepare a new material combining synergistically the properties of the components of the blend. However, the manifestation of superior properties depends on compatibility of homopolymers at the molecular level.

Various methods were described to prepare conductive blends, such as mechanical mixing^[2], casting of a solution containing the components of the blend^[3] or polymerization of one polymer in the presence of the other either by chemically or electro-chemically. Due to the lack of having good mechanical properties and processability, conducting polymers are widely investigated in combination with insulating matrix as composites or blends.

The insertion of a conductive polymer into a dielectric matrix to form a blend has been of interest for many scientists. Conductive polymers can offer a variety of benefits to the host matrix such as variable conductivity, better thermal stability and mechanical properties^[4]. Some examples are reported in the literature such as polyaniline/polyisoprene blend for a biosensor application^[5], an electrically conductive heterogeneous binary polymer blend based on ethylene-propylene-diene-monomer and polyaniline^[6], TiO_2 embedded poly(dimethylsiloxane) gels for actuator applications^[7] and polythiophene/polyisoprene electrorheological (ER) active elastomer blend as a substitute for artificial muscles^[8]. So, the blends can be fabricated with controlled levels of electrical conductivity (σ), suitable for ER studies ($1 \times 10^{-5} > \sigma > 1 \times 10^{-8} \text{ S}\cdot\text{cm}^{-1}$), while retaining the

* This work was financially supported by Turkish Scientific and Technological Research Council (No. 107 T 711).

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Received January 14, 2011; Revised March 21, 2011; Accepted March 22, 2011

doi: 10.1007/s10118-012-1091-9

desired mechanical properties of the polymer matrix^[9].

ER fluids are smart materials composed of micron-sized polarizable solid particles dispersed in a non-polar liquid medium such as mineral oil or silicone oil, the rheological properties of which are drastically changed by applying external electric field strength^[10]. They can switch from a liquid material to a solid-like structure within a millisecond under electric field, repeatedly and reversibly. The suspended particles become polarized due to the external electric field strength applied and formation of chain-like fibrillar structures occur along the direction of the electric field between the upper and lower plates of the electro-rheometer. These stripes formed by the polarized particles are held together by the interparticle electrostatic forces^[11]. Because of their rapid response (< 10 ms) to electric field and simple control, ER fluids have attracted much interest for applications in various devices such as clutches, vibration dampers, actuators and several vibration control systems^[12].

Lately, various semiconducting polymers were often used as ER materials due to their many advantages such as thermal stability, controllable conductivity, lower density, low cost and easy handling reasons. Therefore, the development of high-performance ER fluids *via* optimizing and tuning conducting polymers has attracted considerable attention in recent years^[13].

Polythiophene (PT) has several advantages over other semiconducting polymer particles. It can be obtained easily with a high yield by an oxidative polymerization and is also chemically stable in air and humid medium both in doped and undoped states^[14, 15]. Furthermore, in addition to its enhanced mechanical processability, in order to get a suitable conductivity range for ER measurements, composites or blends could be easily prepared using PT.

To the best of our knowledge, there are no reports in the literature on ER and creep-recovery behaviors of conducting PT/polyoxymethylene (POM)-blend/silicone oil (SO) suspension system. The objective of this research was to investigate the ER properties of easily prepared conductive blend suspension system with a suitable range of conductivity for ER studies. Thus, conducting PT/POM-blend/SO suspension system was successfully prepared. Conductivity, sedimentation ratios, ER properties and creep-recovery response of the material were investigated under various conditions. Further, the results obtained are compared with the ER properties of PT/SO and conducting POM/PT-composite/SO suspension systems, which were also investigated previously in our laboratory^[16].

EXPERIMENTAL

Materials

Poly(oxymethylene); POM [$\text{CH}_3\text{CO}_2(\text{CH}_2\text{O})_n\text{COCH}_3$, acetate end-capped, T_g : -13°C , T_m : 175°C , melt flow index: 1 g/10min ($190^\circ\text{C}/1.05$ kg), form: pellets, hardness: 94 (ASTM D 785), density: $1.42\text{ g}\cdot\text{cm}^{-3}$], thiophene (freshly distilled under vacuum), anhydrous FeCl_3 , CHCl_3 , *N,N*-dimethylformamide (DMF) and silicone oil ($\rho = 0.965\text{ g}\cdot\text{cm}^{-3}$, $\eta = 1000\text{ mPa}\cdot\text{s}$, $\varepsilon = 2.61$ at 25°C) were provided from Aldrich, and used as received.

Preparation of PT/POM Blends

A known amount of PT, prepared by chemical polymerization using FeCl_3 as an oxidizing agent, was added into a flask containing DMF at 55°C . POM was dissolved in DMF in a separate flask and added into the previously prepared PT/DMF suspension. The mixture was stirred for 3 h at 55°C and further 17 h at ambient temperature. After completion of the blending process, PT(50)/POM(50)-blend was filtered, washed with water and ethanol, respectively and dried in a vacuum oven. The main difference between the POM/PT conducting composite and PT/POM conducting blends is in their preparation procedure, which ultimately affects their morphologies. On the other hand, during the synthesis of POM/PT composite, commercially available POM was first dissolved in DMF and then FeCl_3 was added and kept stirring. Then the thiophene/DMF solution was added in to the above solution and the composite formation completed by *in situ* polymerization of thiophene in the POM/DMF solution.

Characterization results revealed that, POM/PT composites showed slightly higher conductivities (*via* bipolaron mechanism) and smoother surfaces than PT/POM blends (as proofed by SEM images). The full

synthesis and characterization of conducting PT/POM blends and POM/PT composites were previously carried out in our laboratory and published elsewhere^[17].

Characterization

The crude PT/POM-blend was ground-milled and subjected to particle size measurement using a Malvern Mastersizer E, version 1.2b particle size analyzer. The data collected were evaluated according to the Fraunhofer diffraction theory by the Malvern software computer^[18]. Then, PT/POM blend was subjected to solid pellet preparation (cylindrical in shape) under 0.5 tons/cm² pressures at ambient temperature. Further, the apparent density, conductivity (by a four probe technique) and dielectric constant (with an HP 4192 A 6F Impedance Analyzer at $f = 1$ kHz) of the blend were measured.

Preparation of Suspensions

Before suspension preparation, particles of the PT/POM-blend and SO were vacuum dried in a vacuum oven for 24 h at 70°C and 110°C, respectively to remove any moisture present. Suspensions of PT/POM-blend were prepared in SO at a series of volume fractions ($\phi = 10\%$ – 20%), by dispersing definite amount of dispersed phase in calculated amount of continuous phase (SO) according to the formula:

$$\phi = \left[\frac{V_{\text{PT/POM particles}}}{V_{\text{PT/POM particles}} + V_{\text{SO}}} \right] \times 100 \quad (1)$$

Sedimentation Ratio Measurements

Determination of the sedimentation ratio which is defined to be proportional to the stability against gravitational forces of the PT/POM-blend/SO suspension system was measured as following: glass tube containing $\phi = 10\%$ volume fraction of the above suspension was immersed into a constant temperature ($T = (25 \pm 0.1)^\circ\text{C}$) water bath. During the neat eye observations, the height of phase separation between the particle-rich phase and the relatively clear oil-rich phase was recorded as a function of time by using a digital composing stick. The percentage sedimentation ratio was defined as the height of the particle-rich phase divided to the total height of suspension as schematically inserted in Fig. 1.

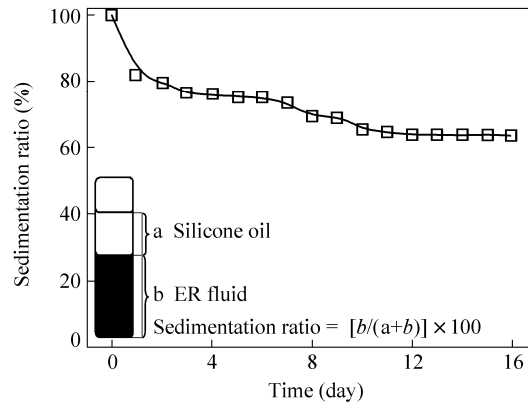


Fig. 1 Sedimentation ratios of PT/POM-blend ($\phi = 10\%$, $T = 25^\circ\text{C}$)

Electrorheological Tests

Flow measurements

Before each measurement to be carried out, PT/POM-blend/SO suspensions were mechanically stirred against sedimentation. Flow rate measurements were carried out between two brass electrodes, which were connected to a high-voltage dc power supply, which is schematically inserted in Fig. 2. The gap between the electrodes was 0.5 cm, the width of the electrodes was 1.0 cm, and the height of the suspensions on the electrodes was 5.0 cm. During the measurements, the electrodes were immersed into a vessel containing the suspensions with a specific

volume fraction and after a few seconds, the vessel was removed and flow time for complete drainage was measured using a digital stopwatch under $E \neq 0$ kV/mm and $E = 0$ kV/mm conditions. This procedure was repeated for various electric field strengths and volume fractions of the suspensions.

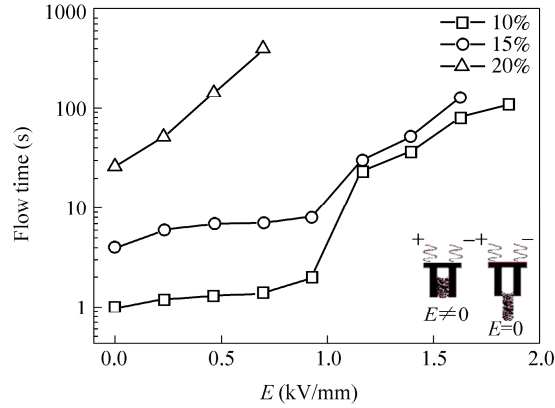


Fig. 2 Effect of electric field strength on flow time ($\phi = 10\%$ – 20% , $T = 25^\circ\text{C}$)

Electrorheometer measurements

ER properties of the suspensions were determined with a Termo-Haake RS600 parallel plate torque rheometer. The gap between the parallel plates was 1.0 mm and the diameters of the upper and lower plates were 35 mm. The potential used in these experiments was supplied by a 0–12.5 kV (with 0.5 kV increments) dc electric field generator (Fug Electronics, HCL 14, Germany), which enabled resistivity to be created during the experiments. All the ER measurements were carried out at constant temperature ($T = 25^\circ\text{C}$), except the temperature sweep ($T = 0$ – 80°C), and at either a controlled rate (CR) or a controlled stress (CS) mode.

Creep and Creep-Recovery Measurements

During the creep and creep-recovery experiment, a constant stress ($\tau_0 = 10$ Pa) was applied instantaneously for 10 s to the PT/POM-blend/SO system at constant conditions ($\phi = 20\%$, $T = 25^\circ\text{C}$, $E = 0$ kV/mm and $E = 2.0$ kV/mm), and change in strain (γ) was measured over a period of time. Then the stress was set to $\tau_0 = 0$ Pa to measure the recoverable elastic portion of the deformation.

RESULTS AND DISCUSSION

Characterization

The average hydrodynamic particle diameter ($d_{h(0.5)}$), density (ρ), conductivity (σ) and dielectric constant (ϵ) of PT/POM-blends were measured to be $d_{h(0.5)} = 24.77 \mu\text{m}$, $\rho = 1.36 \text{ g}\cdot\text{cm}^{-3}$, $\sigma = 3.85 \times 10^{-5} \text{ S}\cdot\text{m}^{-1}$ and $\epsilon = 26.75$, respectively. These values were decided to be in a suitable range for ER measurements^[19]. In our previous investigation, carried out on conducting POM/PT-composites^[16], decreasing average hydrodynamic particle size, density, conductivity and dielectric constant values were monitored with increasing PT content, which may be attributed to the formation of much more compatible material with POM/PT-composite, when compared to the PT/POM-blend.

Sedimentation Ratio of the Suspensions

Stability of the ER fluids against sedimentation is one of the very important factors from industrial and application points of view. When the density of particles is not the same as that of the medium, the particles with micron size settle down according to Stoke's law^[20]. There are two main factors which affect the sedimentation stability of suspensions against gravitational forces: (i) the density mismatch between the base fluid and dispersants, (ii) the average sizes of the dispersed particles. The change in sedimentation ratio with time for

PT/POM-blend/SO suspension system is given in Fig. 1. At the end of 16 days of observation, 64% of PT/POM-blend suspended particles was determined to remain unsettled ($\varphi = 10\%$). The other volume fractions ($\varphi = 15\%$ and 20%) prepared for ER measurements were also subjected to sedimentation ratio measurements, but it was impossible to distinguish a phase separation. In our previous study, a sedimentation ratio of 81% and 97% were observed for conducting POM/PT-composite/SO ($c = 10$ wt%, $\rho = 1.003$ g·cm⁻³, $d_{h(0.5)} = 29.54$ μm) and PT/SO ($c = 5$ wt%, $\rho = 0.662$ g·cm⁻³, $d_{h(0.5)} = 25.36$ μm) suspension systems, respectively at the end of 16 days^[16]. Increasing sedimentation ratios were also reported with decreasing particle sizes and densities in the literature for various systems^[21].

Flow Measurements

To observe the effect of dc electric field on the ER activity, flow rate measurements were carried out on PT/POM-blend/SO suspensions. For this purpose, PT/POM-blends were prepared at a series of particle volume fractions ($\varphi = 10\%$ – 20%) in SO and flow times were measured under $E \neq 0$ kV/mm and $E = 0$ kV/mm conditions (Fig. 2). From the flow measurements, change in the threshold energies (E_t , the first significant increment of flow time under E) with volume fractions are determined to be as following: $(E_t = 1.16$ kV/mm) $_{\varphi = 10\%} > (E_t = 0.9$ kV/mm) $_{\varphi = 15\%} > (E_t = 0.23$ kV/mm) $_{\varphi = 20\%}$. During the flow time measurements, it was concluded that electric field response time decreases with increasing volume fractions as a result of stripe formation between the electrodes^[22].

Electrorheological Studies

Effect of electric field strength and volume fraction on ER activity

Figure 3 shows the change of electric field induced viscosity (η_E) and shear stress (τ) with electric field strength (E) and volume fraction (φ) for the suspensions. The electric field viscosity of suspensions increased almost slightly for $\varphi = 10\%$ and 15% and linearly for $\varphi = 20\%$ with increasing electric field strength up to $E = 2$ kV/mm and decrease in the values of electric field viscosity was observed at higher electric field strengths.

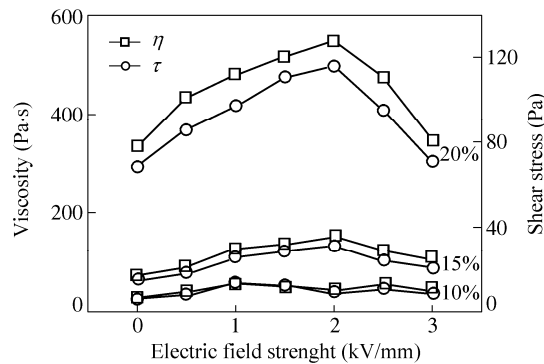


Fig. 3 Change in electric field viscosity and shear stress with electric field ($\varphi = 10\%$ – 20% , $\dot{\gamma} = 1.0$ s⁻¹, $T = 25^\circ\text{C}$)

It can be said that the electrical response of the PT/POM-blend/SO suspension is significant for $\varphi = 20\%$ volume fraction, which is consistent with the flow time measurements as discussed above. The maximum electric field viscosity was recorded to be 549 Pa s for PT/POM-blend/SO suspension system at $E = 2$ kV/mm for $\varphi = 20\%$ volume fraction. The results suggest that at low volume fractions the number of particles is modest and the particles are far away from each other to allow significant interparticle interactions. On the other hand, at higher volume fractions, the distances between particles get closer and hence stronger interparticle interactions take place, which undergoes to the formations of electric field-induced dipole moments, stronger stripes between the plates and higher resistance against flow. The magnitude of this polarization force (F_p) in the direction of electric field (E) is^[23]:

$$F_p = \frac{6\epsilon r^6 E^2}{h^4} \quad (2)$$

where ϵ is the dielectric constant of the particle, h is the distance between particles, and r is the radius of the particle. An increased suspension volume fraction will decrease the distance between the particles, which will result in an increased polarization force. A similar stripe formation of alumina and barium titanate suspensions was clearly demonstrated in a study by Kittipoomwong *et al.*^[22] as a function of time at various field strengths at constant shear rate.

Decrease of electric field viscosity at $E > 2$ kV/mm may be attributed to the following reasons: (i) the particles are forced to get closer to each other at high electric field strengths, (ii) the electrical double layers around particles overlap, (iii) the mutual action (interactional movement of the particles under external electric field strength) between particles increases, (iv) the electrical double layers may drop out of the particles, which may undergoes to instantaneous partial discharge and ends up with decreased ER activity.

Shear stress is one of the critical design parameters in ER phenomenon and has attracted considerable attention both theoretically and experimentally^[24]. Electric field induced shear stress (τ_E) of conducting PT/POM-blend/SO suspension system was observed to increase with increasing volume fraction and reached to $\tau_E = 116$ Pa at $E = 2$ kV/mm (Fig. 3). Slight decreases in the value of the τ_E were observed at the electric field strengths bigger than 2 kV/mm. Hence, $E = 2$ kV/mm was decided to be the optimum electric field strength to obtain the highest τ_E values.

Several models have been proposed to describe the ER phenomena *via* shear stress equations. The original model is called “polarization model” which attributes the ER phenomena to the attractive force acting between the dispersed particles. This polarization model shows excellent agreement with the data for small volume fractions (ϕ) and electric field strengths (E).

$$\tau_E \propto \phi K_f E^2 \beta^2 \quad (3)$$

where, $\beta = (K_p - K_f)/(K_p + 2K_f)$ is the dimensionless dielectric mismatch parameter at dc or low frequency ac fields given by Conrad^[25] and Davis^[26]. Here, K_p and K_f are the dielectric permittivity of the particle and the fluid, respectively. As an electric field is applied, electrical dipole moments and the electrostatic interactions between the conducting PT/POM-blend particles are induced leading to an interparticle interaction acting like an electrical network. In addition, a voltage differential between the upper and lower plates of the electro-rheometer can generate electromagnetic forces that act to pull the electrodes together. This attraction causes a compressive force on the conducting-PT/POM-blend particles in the direction of the electric field throughout the gap between the electrodes which consequently cause an increase in the τ_E values of the suspension. When compared to PT/SO and POM/PT-composite/SO suspension systems, higher electric field viscosity values were observed with the conducting PT/POM-blend/SO suspension system at higher volume fractions and electric field strengths as expected^[16].

Effect of shear rate on shear stress and viscosity

The viscosity (η) of conducting PT/POM-blend/SO system was observed to decrease with increasing shear rate ($\dot{\gamma}$) with typical curves of shear thinning non-Newtonian viscoelastic behavior both under $E = 0$ and $E = 2$ kV/mm conditions (Fig. 4). The viscosity of the PT/POM-blend/SO system became independent of shear rate at higher shear rate values. The hydrodynamic interactions and the viscous forces (F_v) affect the particles in a suspension. The magnitude of these viscous forces is expressed as:

$$F_v = 6\pi\eta r^2 \dot{\gamma} \quad (4)$$

The shear thinning behaviors of the suspensions may be attributed to the dominant character of deformation rate of the ER-fibrils to the reformation rate at the high shear rate values under E . Although the viscous forces are proportional to the shear rate, at higher shear rates the electric field viscosity (η_E) becomes less dependent on

the electric field strength. This suggests that at higher shear rates, F_v becomes dominant to the F_p , and the suspensions' structures do not vary appreciably with the magnitude of E .

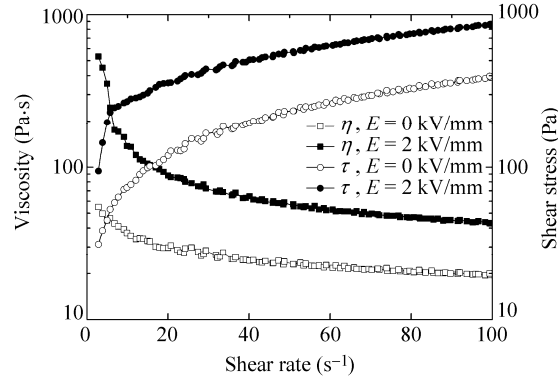


Fig. 4 Effect of shear rate on shear stress and viscosity ($\phi = 20\%$, $T = 25^\circ\text{C}$)

The electric field induced shear stress (τ_E) of the suspensions was observed to increase with increasing shear rate and reached to $\tau_{E=2 \text{ kV/mm}} = 861 \text{ Pa}$ at $\dot{\gamma} = 100 \text{ s}^{-1}$, which was 46% higher than the zero field shear stress value ($\tau_{E=0 \text{ kV/mm}} = 397 \text{ Pa}$). In contrast to the conducting POM/PT-composite^[16], Bingham flow behavior was observed under both $E = 0$ ($\tau_{\text{yield}} = 54 \text{ Pa}$) and $E = 2 \text{ kV/mm}$ ($\tau_{\text{yield}} = 227 \text{ Pa}$) conditions for PT/POM-blends. This is due to the plasticizing effect of POM component in PT/POM-blends, in which these two components are mixed homogeneously at macro level and result in higher interactions *i.e.* dispersive forces, when compared to the homogeneously distributed PT particles in POM matrix in POM/PT-composites^[16]. On the other hand, smaller yield stress ($\tau_y = 65 \text{ Pa}$ at $E = 2 \text{ kV/mm}$) value was reported by Chotpattananont *et al.*, for perchloric acid doped poly(3-thiophene acetic acid)/SO suspension system^[27].

Effect of temperature on ER activity

Temperature effect on ER performance is one of the critical parameters, and sustained ER activity over a range of temperature is required from the industrial point of view. To investigate the behavior of materials at elevated temperatures, a temperature sweep at a rate of 0.1 K/s was carried out in the range of $0\text{--}80^\circ\text{C}$ for conducting PT/POM-blend/SO system (Fig. 5). Gradual shear stress loss ($\Delta\tau_E$) was observed with a small magnitude of $\Delta\tau_E = 11 \text{ Pa}$. Higher shear stress losses were determined for conducting POM/PT-composite/SO ($\Delta\tau_E = 513 \text{ Pa}$) and PT/SO suspension ($\Delta\tau_E = 545 \text{ Pa}$) systems at $T = 0\text{--}100^\circ\text{C}$ in our previous study^[16]. These results revealed that conducting PT/POM-blend/SO system was more resistant against elevated temperature than conducting POM/PT-composite/SO system. These results may be attributed to the following reasons: (i) the difference in their conductivities ($\sigma_{\text{POM/PT-composite}} 2.32 \times 10^{-2} \text{ S}\cdot\text{m}^{-1} > \sigma_{\text{PT/POM-blend}} 3.85 \times 10^{-5} \text{ S}\cdot\text{m}^{-1}$), since enhanced kinetic energies of the particles at elevated temperatures cause weakly formed electric field induced-oriented fibrillar structures (stripes) between the upper and lower plates of the electrorheometer, and this effect is more dominant on highly conductive materials as in the case of POM/PT-composite, (ii) the difference in their dielectric constants ($\epsilon_{\text{POM/PT-composite}} 5.98 < \epsilon_{\text{PT/POM-blend}} 26.75$), (iii) the difference in the thermal motion of dispersed particles in SO: the ER performance loses at high medium viscosity and high ER fluid volume fractions due to large frictional forces as reported in the literature by Kim *et al.*, for polyaniline/SO suspensions, indicating the difficulty of the dispersed particles to turn along the direction of the electric field strength and to form columnar chains or stripes at these hard conditions^[28]. It is concluded that, the ultimate ER performance comes from the balance among these factors, which ultimately decreases the ER performance of conducting PT/POM-blend/SO systems at elevated temperatures.

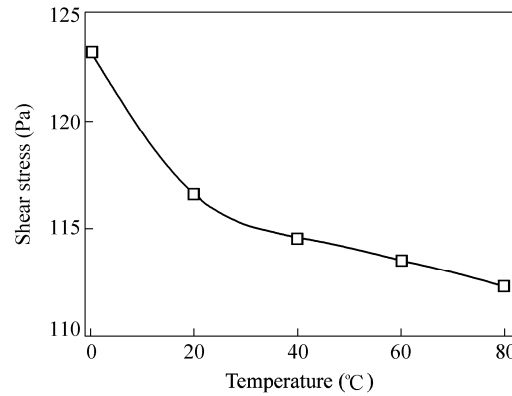


Fig. 5 Effect of temperature on shear stress ($\phi = 15\%$, $\dot{\gamma} = 1.0 \text{ s}^{-1}$, $E = 2 \text{ kV/mm}$)

Effect of frequency on elasticity modulus

The external frequency (f) is an important factor for characterizing the dynamic viscoelastic properties of ER fluids^[29]. Figure 6 shows the change in elasticity modulus (G') and viscous modulus (G'') with frequency under $E = 0 \text{ kV/mm}$ and $E = 2 \text{ kV/mm}$ conditions. Stress sweep was first carried out to determine the proper stress value to measure the G' and the G'' in the linear viscoelastic regime. The appropriate stresses were 0.4 Pa and 6 Pa for $E = 0 \text{ kV/mm}$ and $E = 2 \text{ kV/mm}$ conditions, respectively. Figure 6 indicates that the G' is higher than the G'' for both conditions examined. In the absence of the electric field, the G' increases with frequency, providing pseudoplastic character due to strong interparticle interactions. Belza *et al.* reported that elastic modulus steeply increases with frequency and becomes dominant as a result of high elasticity of the system with increasing particle concentration under $E = 0 \text{ kV/mm}$ for the urea-modified silica particles in SO^[30]. With the existence of the electric field, ($E = 2 \text{ kV/mm}$) for PT/POM-blend/SO system, the G' was observed to increase significantly when compared to $E = 0 \text{ kV/mm}$ and remained approximately constant in the whole frequency range. It can be predicted that an ER fluid composed of conducting PT/POM-blend behaves like a viscoelastic solid-like material in the linear viscoelastic region at the applied stress level ($\tau = 6 \text{ Pa}$), having a vibration damping capability, due to the formation of electric field induced-stripe structures, which do not relax at a given range of frequency^[31]. The electric field induced-interparticle interactions induce the PT/POM particles between upper and lower plates of the electrorheometer, which undergoes to fibril formation and higher stripe rigidity occurs, as indicated by enhanced elasticity modulus values. For PT/SO and POM/PT-composite/SO suspension systems, the G' under $E = 1 \text{ kV/mm}$ and $\tau = 10 \text{ Pa}$ conditions was observed to show slight increase up to 46.4 Hz and showed sharp increase after 70 Hz^[16].

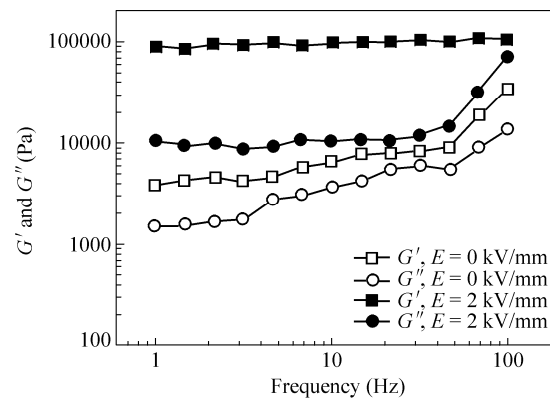


Fig. 6 Change in elasticity modulus (G') and viscous modulus (G'') with frequency ($\phi = 20\%$, $T = 25^\circ\text{C}$)

Creep and creep-recovery tests

The creep and creep-recovery experiments are very suitable tools to get insights into the interactions, which influence the mobility of molecules and the mechanistic origin of the flow of a material under time dependent deformations^[32, 33]. To obtain creep and creep-recovery response (reorganization of the polymer chains after deformation), the conducting PT/POM-blend/SO system is subjected to an instantaneously applied constant shear stress ($\tau_0 = 10$ Pa) at controlled stress (CS) mode, under $E = 0$ kV/mm and $E = 2$ kV/mm, while strain (γ) is monitored over a period of time ($t = 10$ s).

It was observed that the creep curves comprise three parts: the instantaneous strain (I), the retardation strain (II), and the viscous strain (III) at this stress level (Fig. 7). When the applied stress was removed ($\tau_0 = 0$ Pa), PT/POM-blend showed an instantaneous elastic recovery (IV). It is apparent that the PT/POM-blend showed a non-linear viscoelastic behavior, since instantaneous strain (region I) is not equal to the instantaneous elastic recovery (region IV). A recoverable strain, which is a reduced strain just after an applied stress is removed, is a measure of the elasticity of viscoelastic materials. The recovery percentages of the conducting PT/POM-blend system are 26% and 41% under $E = 0$ kV/mm and $E = 2.0$ kV/mm conditions, respectively. It can be confirmed that the elasticity of the system becomes superior to its viscosity under E ^[34]. On the other hand, for PT/SO system the viscoelastic creep behavior and for conducting-POM/PT-composite/SO system the elastic recovery, viscoelastic recovery and unrecovered viscous flow regions were determined in our previous study^[16]. These results are inconsistent with the viscoelastic creep-recovery behavior reported for polypyrrole and poly(ethylene-co-methyl methacrylate) by Genovese and Shanks^[35].

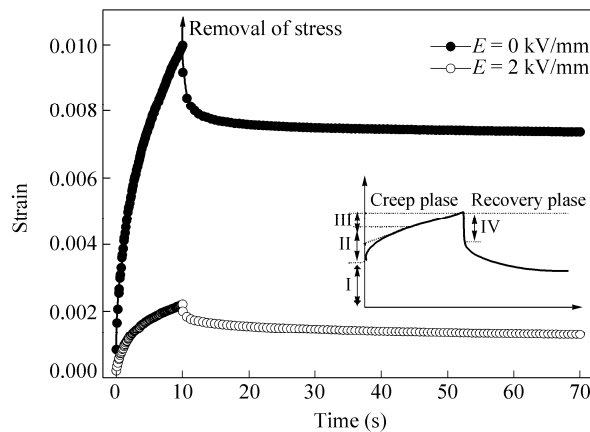


Fig. 7 Creep and creep-recovery response of PT/POM-blend ($\phi = 20\%$, $T = 25^\circ\text{C}$)

CONCLUSIONS

Antis sedimentation stability of the conducting PT/POM-blend/SO system was observed to be suitable for potential industrial applications. ER activities of the suspensions were observed to increase with increasing electric field strength and volume fraction and with decreasing temperature and shear rate, and a typical shear thinning non-Newtonian viscoelastic behavior was also observed. In addition, it could be said that conducting PT/POM-blend/SO systems were more resistant against elevated temperature than conducting POM/PT-composite. Elasticity modulus was observed to show vibration damping capability. Non-linear recoverable viscoelastic creep-recovery behavior was observed for conducting PT/POM-blend/SO systems.

ACKNOWLEDGEMENTS The authors thank to the scholarship provided for O. Erol (BIDEB).

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