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ORIGINAL CONTRIBUTION

Young Dae Kim
Dong Hyup Park

The electrorheological responses of suspensions of polypyrrole-coated polyethylene particles

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Y.D. Kim (✉) · D.H. Park
Faculty of Applied Chemistry,
Chonnam National University,
300 yongbong-dong,
Kwangju 500–757, Korea
E-mail: youngdae@chonnam.ac.kr
Tel.: +82-62-5301897
Fax: +82-62-5301879

Abstract The electrorheological (ER) responses of polypyrrole (PPy)-coated polyethylene (PE) suspensions in mineral oil were investigated. PPy was coated on PE particles to enhance the particle polarization by increasing the particle surface conductivity, which would lead to an enhanced ER response. The ER response of the PPy-coated PE suspensions is greatly enhanced compared to that of the PE suspension. The dielectric properties of the corresponding suspensions show that the ER enhancement arises from the enhanced particle polarization. Various PPy-coated PE particles were synthesized by controlling the amount of pyrrole or $FeCl_3 \cdot 6H_20$ during the pyrrole polymerization, and the ER responses of their suspensions were investigated. The ER response initially increases with the amount of pyrrole or $FeCl_3 \cdot 6H_20$, passes through a maximum, and then decreases with the amount of pyrrole or $FeCl_3 \cdot 6H_20$. The increase in the ER response with amount of pyrrole or $FeCl_3 \cdot 6H_20$ is due to the enhanced particle polarization with the increased particle surface conductivity. The decrease in the ER response at large amounts of pyrrole or $FeCl_3 \cdot 6H_20$ arises from the increased conduction between the PPy-coated PE particles. Poly(vinyl alcohol) was coated on the PPy-coated PE particles to restrict the increased conduction. The ER response is greatly enhanced by the poly(vinyl alcohol) coating on the PPy-coated PE particles, suggesting that the effective ER suspensions can be prepared by both enhancing the particle surface conductivity and restricting the increased conduction.

Keywords Electrorheology · Polypyrrole-coated particle · Polypyrrole · Suspension · Double coating

Introduction

Electrorheological (ER) response is defined as the dramatic change in rheological properties of a suspension of small particles owing to the application of a large electric field transverse to the direction of flow. ER suspensions are typically composed of nonconducting or semiconducting particles dispersed in a nonconducting continuous phase. A large ER effect was first reported by Winslow in 1949 [1] and has been reviewed in several publications [2, 3, 4, 5]. The simplicity of engineering designs based on ER materials has facilitated the development of specifications for a broad range of devices, such as dampers, clutches, and adaptive structures [3]. Although many ER devices have been brought successfully to the prototype stage, and despite much industrial activity, the anticipated commercialization of these devices has yet to be realized. The main limitation of ER technology development is the lack of effective suspensions [5].

Various mechanisms have been proposed to explain the ER response. Electro-osmosis mechanism suggests that the ER response arises from the formation of a water bridge between the particles [6]. The interelectrode circulation mechanism proposes that the interelectrode circulation of particles between the electrodes, due to the particle charge change by electrochemical reactions at the electrode surface, leads to the ER response [2]. The electric double layer mechanism proposes that the origin of the ER response is the overlap of electric double layers [7]. The electrostatic polarization model explains that the ER response arises from the electrostatic interactions between the particles due to the field-induced polarization of the particles [8, 9]. Among these mechanisms, the electrostatic polarization model seems to be the most suitable explanation for the ER phenomena.

Activators are often used to activate suspensions. Some suspensions display little or no ER activity unless a small amount of water or surfactant is added, while other suspensions exhibit a significantly enhanced ER response with activator present [6, 10, 11, 12, 13]. Enhancing ER activity with activators such as water severely limits the allowable temperature range of operation, promotes corrosion, and increases power consumption. Therefore, it is necessary to design ER suspensions which show a high ER response without the limitations imposed by introducing activators.

Recently, anhydrous ER suspensions using polymer particles [14], inorganic–organic composite particles [15], and semiconducting polymer particles [14, 16, 17, 18, 19] were reported. The ER suspensions of semiconducting polymer (such as polyaniline [16], copolyaniline [17], copolypyrrole [18], poly(styrene-*co*-divinylbenzene) [14], and acene quinone radical polymers [19], etc.) particles showed good ER responses.

In this work, we investigated the ER response and dielectric properties of the suspensions of polypyrrole (PPy)-coated polyethylene (PE) particles. PPy was coated on PE particles to enhance the particle polarization by increasing the particle surface conductivity, which would lead to an enhanced ER response. It was reported that the increased particle surface conductivity enhanced the particle polarization and hence increased the ER response [12, 13]. PPy-coated PE particles were synthesized by the pyrrole polymerization on PE particles. Various PPy-coated PE particles were synthesized by controlling the amount of pyrrole or $FeCl_3 \cdot 6H_20$ during the pyrrole polymerization, and the ER responses and dielectric properties of their suspensions were investigated. Also, poly(vinyl alcohol) (PVA) was coated on the PPy-coated PE particles to restrict the increased conduction between the particles.

Experimental

PE particles (2.5 g, Aldrich) were dispersed in 200 ml deionized water containing 1.0 g methylcellulose (Showa Chemical) in a round-bottomed flask fitted with a magnetic stirrer. $FeCl_3 \cdot 6H_20$ (Kanio Chemical) dissolved in 50 ml deionized water was slowly added to the PE particle dispersed solution. Pyrrole (Acros Chemical) was added and the polymerization was allowed to proceed at 25 °C for 24 h while stirring. Pyrrole was purified by passing it through a column of activated basic alumina and was stored at –15 °C prior to use. The black PPy-coated PE particles were filtered and washed several times with deionized water to remove by-products of the pyrrole polymerization. The particles were dried in a vacuum oven at 50 °C for 24 h. The particle sizes of PE and PPy-coated PE particles were measured using a particle size analyzer (Malvern PSA). The average diameters of the PE particles and the PPy-coated PE particles were 45 and 50 µm, respectively. Scanning electron microscopy (SEM) images of the PE and PPy-coated PE particle surfaces are shown in Fig. 1a and b, respectively. Cracks and rough regions on the PE particle surface are coated with PPy and as a result the PPy-coated PE particles have relatively smooth particle surfaces, indicating that the PE particle surface is effectively covered with PPy.

ER suspensions were prepared by dispersing PPy-coated PE particles in mineral oil (Sunkyung Chemical, $\eta_c = 180$ cP, $\rho_c = 0.85$ gcm^{-3}) and were stored in a desiccator to minimize contact with air. The suspensions were allowed to equilibrate for at least 24 h before the experiments. The mineral oil was stored for

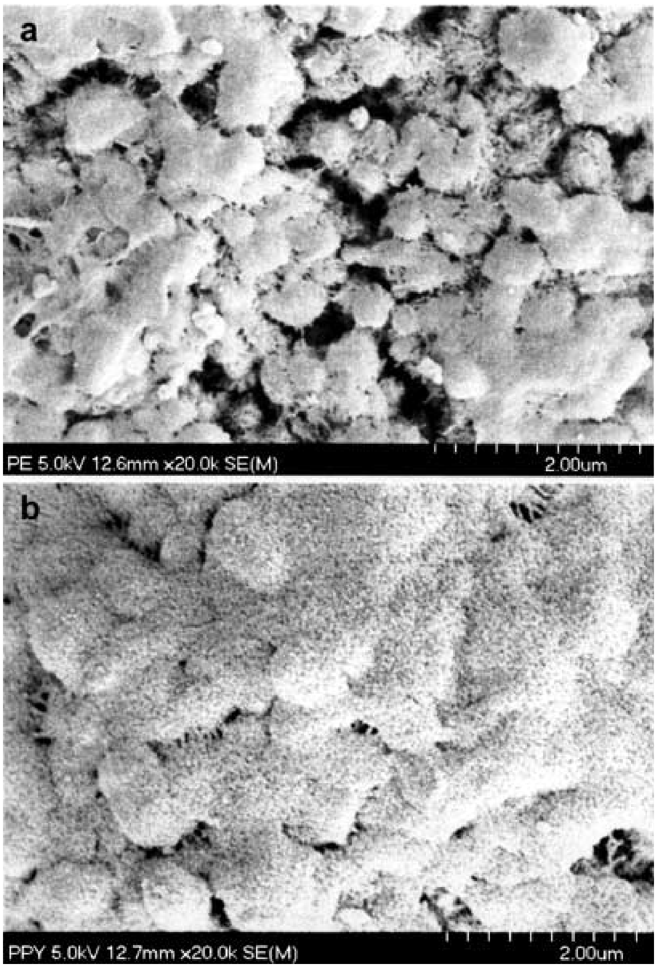

Fig. 1. Scanning electron microscopy micrographs of the particle surface of **a** polyethylene (*PE*) particles (×20,000) and **b** polypyrrole (*PPy*)-coated PE particles (×20,000)

more than 1 week over molecular sieves and was then used for all the rheological and dielectric measurements.

Rheological experiments were performed at 25 °C using a Rheometric ARES rheometer fitted with parallel plates and modified for the application of high electric fields. Potential differences were supplied by a high-voltage direct current power supply. The samples were placed between the parallel plates and sheared for 1 min at a high shear rate (above 40 s^{-1}) and zero field strength to ensure a uniform particle distribution. The desired electric field was then applied for 1 min with no shear prior to the measurements. Rheological measurements were performed by shearing the suspension at a constant shear rate under the applied electric field and recording the shear stress transmitted by the suspension. Experiments were performed with decreasing and increasing shear rates to obtain plots of the shear stress as a function of the shear rates. Values for the dynamic yield stress were determined by extrapolating the shear stress–shear rate data to zero shear rate.

Suspension capacitance and loss were measured using a Fluke impedance analyzer (Fluke 6306A RLC meter), which probes frequencies in the range 50 Hz–100 kHz and operates with potential differences in the range 0.01–1.0 V (root mean square). A three-terminal, guarded dielectric cell was employed. Suspension dielectric constants and dissipation factors were determined for decreasing and increasing field frequencies. The conductivities of the PPy-coated PE particles were measured by the two-probe method using compressed disks with a picoammeter (Keithley 485).

Results and discussion

The ER behavior under various electric field strengths is presented in Fig. 2 for a 10 wt% PPy-coated PE suspension in mineral oil. The PPy-coated PE particles were synthesized by using 0.1 g pyrrole and 1.5 g $FeCl_3{\cdot}6H_20$. Without an electric field, the suspension behaves like a Newtonian fluid with the slope of the logarithm of the shear stress to the logarithm of the shear rate of 1.0. By applying an electric field to the suspension, the shear stresses for the ER suspension dramatically increase and even the suspension shows a yield stress, showing shear-thinning behavior. The shear stresses and yield stress increase with the increase in the electric field strength. The steady-shear rheological response can be described as that of Bingham fluid, showing the prevalent features of the ER response – an apparent yielding phenomenon at low shear rates and shear-thinning behavior approaching a constant viscosity at high shear rates. It was also observed by using a charge-coupled-device camera that the ER response was related to the electric field-induced alteration of the suspension structure, where strands of particles formed spanning the electrode gap under the applied electric field. At intermediate shear rates (5–50 s^{-1}), however, anomalous behavior where the shear stress decreases with shear rate is observed. The anomalous behavior might arise from a negative synergistic interaction between hydrodynamic and polarization forces.

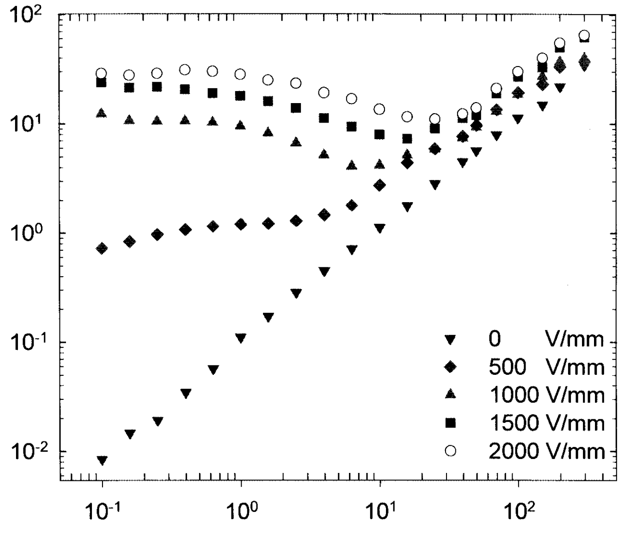

Fig. 2. Shear stress as a function of shear rate for 10 wt% PPy-coated PE suspension in mineral oil (pyrrole = 0.1 g and $FeCl_3{\cdot}6H_20 = 1.5$ g)

Marshall et al. [20] showed that the dependence of the suspension viscosity on the electric field strength and the shear rate could be combined into a single curve in terms of the Mason number, $Mn = \eta_c\dot{\gamma}/2\varepsilon_0\varepsilon_c(\beta E)^2$ and the rheological data were correlated with the Bingham constitutive equation:

$$\frac{\eta_\infty}{\eta - \eta_\infty} = \frac{Mn}{Mn^*} \quad . \tag{1}$$

Here, η_c is the viscosity of the continuous phase, $\dot{\gamma}$ is the shear rate, ϵ_0 is the permittivity of free space, ϵ_c is the dielectric constant of the continuous phase,E is the applied electric field strength, η_∞ is the high-shear-rate viscosity of the suspension under no electric field, and Mn^* is a material property of the suspension depending on the dielectric properties and the volume fraction. The term $\beta = (\epsilon_p - \epsilon_c)/(\epsilon_p + 2\epsilon_c)$ is the relative polarizability of the particle, where ϵ_p is the particle dielectric constant. Mn is a measure of the relative importance of the hydrodynamic and polarization forces.

As shown in Fig. 3, the data in Fig. 2 reduce to a single linear curve with the slope of 1.0 well approximated by Eq. (1). Mn^* is found to be 0.48 by performing a least-squares fit of the data. At low shear rates ($Mn \ll 1$), polarization forces are dominant over hydrodynamic forces. The stress is determined by polarization forces and the shear stress is independent of shear rate, showing a plateau (Fig. 2). At high shear rates ($Mn \gg 1$), hydrodynamic forces are dominant. Therefore, the stress arises from purely hydrodynamic forces and the suspension viscosity is independent of the electric field strength, leading to a Newtonian behavior – the shear stress is proportional to shear rates and suspension viscosities at various electric fields approaching η_∞.

When polarization forces and hydrodynamic forces are comparable (e.g., at intermediate shear rates,

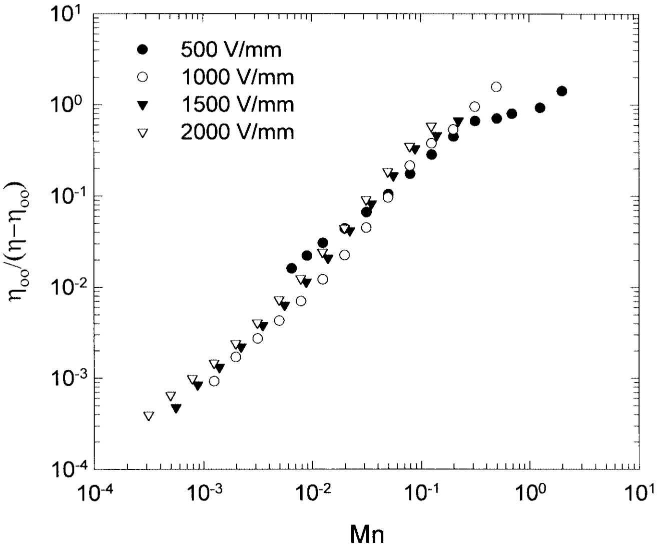

Fig. 3. Relative suspension viscosity as a function of Mason number at several electric field strengths

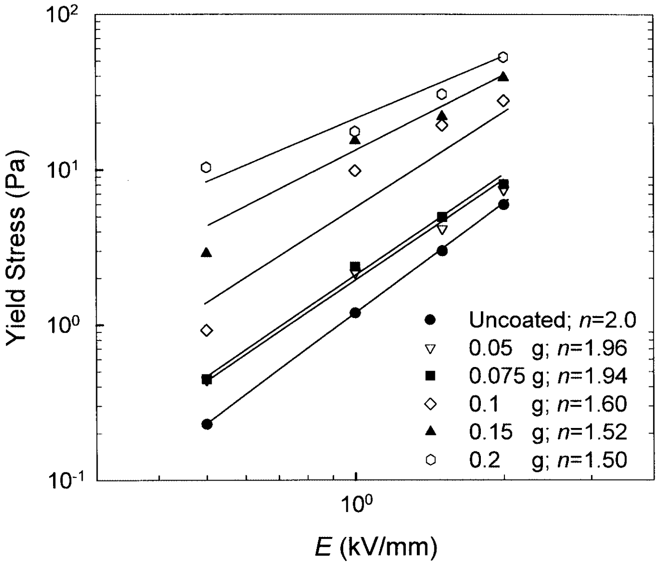

Fig. 4. Yield stress as a function of electric field strength for 10 wt% various PPy-coated PE suspensions in mineral oil ($FeCl_3{\cdot}6H_20$ = 1.5 g, *symbols*: amount of pyrrole, *n* is the slope of the regression line)

$Mn^*/Mn \approx 1$), they might influence indirectly each other, leading to a synergistic or negative synergistic interaction. The indirect influence seems to arise from the dynamics of structural rearrangements. At low Mn, the stress arises from breaking particle strands between the electrode gap. With increasing shear rate, hydrodynamic forces begin to influence the structure of the particle strands, forming particle strand aggregates owing to the rearrangements of the particle strands. The formation of particle strand aggregates was observed during the rheological measurement of the PPy-coated PE suspension (0.1 g pyrrole and 3.0 g $FeCl_3{\cdot}6H_20$). The formation of particle strand aggregates at intermediate shear rates may cause the negative synergistic interaction, leading to the shear stress decrease with shear rate. The change in the shear stress at intermediate shear rates was considered to result from the formation of small strandlike aggregates [9] or from swirling motion [16, 21]. Since anomalous behavior occurs when $Mn \approx Mn^*$; we can estimate the critical shear rate, $\dot{\gamma}_c = 2\varepsilon_0\varepsilon_c(\beta E)^2 Mn^*/\eta_c$, at which the shear stress shows anomalous behavior. The values of $\dot{\gamma}_c$were estimated to be in the range 9–90 s^{-1} and increased with the electric field strength, consistent with Fig. 2.

The dependence of the dynamic yield stress on the electric field strength is presented in Fig. 4 for 10 wt% PPy-coated PE suspensions of various PPy-coated particles. The PPy-coated PE particles were synthesized by using various amounts of pyrrole and 1.5 g $FeCl_3{\cdot}6H_20$. The symbols represent experimental data and the lines indicate the linear regression of the data. Compared to the yield stresses of the uncoated PE suspension, those of the PPy-coated PE suspensions are greatly enhanced by coating PPy on the PE particles. The dynamic yield stress is the plateau stress at very low shear rates ($Mn \ll 1$) and is related to polarization forces. The polarization force per pair interaction is given by [9]

$$F = 12\pi\varepsilon_0\varepsilon_c a^2\beta^2 E^2, \tag{2}$$

where a is the particle radius. Therefore, the ER response (e.g., yield stress) will increase on enhancing the relative polarizability, β, and hence the particle polarization, which is related to ϵ_p. The particle polarization will increase with the coating of a semiconducting polymer (e.g., PPy) on the particles, since the particle surface conductivity increases owing to the high conductivity of the coated semiconducting polymer. It was reported that the particle polarization was enhanced by the increased particle surface conductivity [12, 13].

The yield stresses increase with the increase in the amount of pyrrole. The increase in the ER response with the amount of pyrrole is due to the enhanced particle polarization with the increasing particle surface conductivity. The conductivities of the PPy-coated particles were measured as 1.82×10^{-9}, 2.25×10^{-9}, 2.36×10^{-9}, 2.61×10^{-9}, and 2.87×10^{-9} Scm^{-1} for 0.05, 0.075, 0.1, 0.15, and 0.2 g pyrrole, respectively, increasing with the amount of pyrrole. Lascelles et al. [22] also reported that the conductivity of PPy-coated polystyrene particles and the PPy coating thickness increased with the amount of pyrrole during the pyrrole polymerization. As the amount of pyrrole increases, the particle surface conductivity increases and hence the ER response is enhanced owing to the enhanced particle polarization.

The dependence of the suspension dielectric properties on the electric field frequency is presented in Fig. 5 for the suspensions in Fig. 4. The dielectric constants of the suspensions increase with the increase in the amount of pyrrole, but the dissipation factors do not show any notable differences. The dielectric constants keep increasing owing to the increasing particle surface conductivity with the amount of pyrrole. Assuming pairwise additivity and only nearest-neighbor interactions, the dynamic yield stress can be represented as [8]

$$\tau = 18\phi\varepsilon_0\varepsilon_c\beta^2E^2f_m\left(1-\frac{(\pi/6)^{1/2}}{(l/a)\tan\theta_m\phi^{1/2}}\right), \qquad (3)$$

where ϕ is the particle volume fraction, l is the electrode separation, f_m is the maximum in the dimensionless restoring force, and θ_m is the angle at the maximum. f_m and θ_m are functions of only ϵ_p/ϵ_c. Therefore, the dynamic yield stress can be estimated from dielectric data. The values of f_m and θ_m were estimated as 0.1126 and 14.8 using the dielectric data in Fig. 5. The experimental values of l and ϕ were 1 mm and 0.091, respectively. The dynamic yield stresses at the electric field strength of 2,000 Vmm^{-1} were estimated from Eq. (3) as 2.57, 2.65, 2.88, 3.07, and 3.35 Pa for 0.05, 0.075, 0.1, 0.15, and 0.2 g pyrrole, respectively. The estimated dynamic yield stresses are not comparable to the experimental data (Fig. 4) and the discrepancy between the experimental and estimated value increases with the increase in the amount of pyrrole. However, the similar behavior of the estimated and experimental dynamic yield stress, increasing with the increase in the particle polarization, indicates that the ER response arises from the electrostatic polarization. The underestimation of the dynamic yield stress may arise from the neglect of the multiple interactions between particles in Eq. (3). Since the particle polarization increases with the amount of pyrrole, the ER response would increase with the increase in the amount of pyrrole, consistent with the rheological data (Fig. 4).

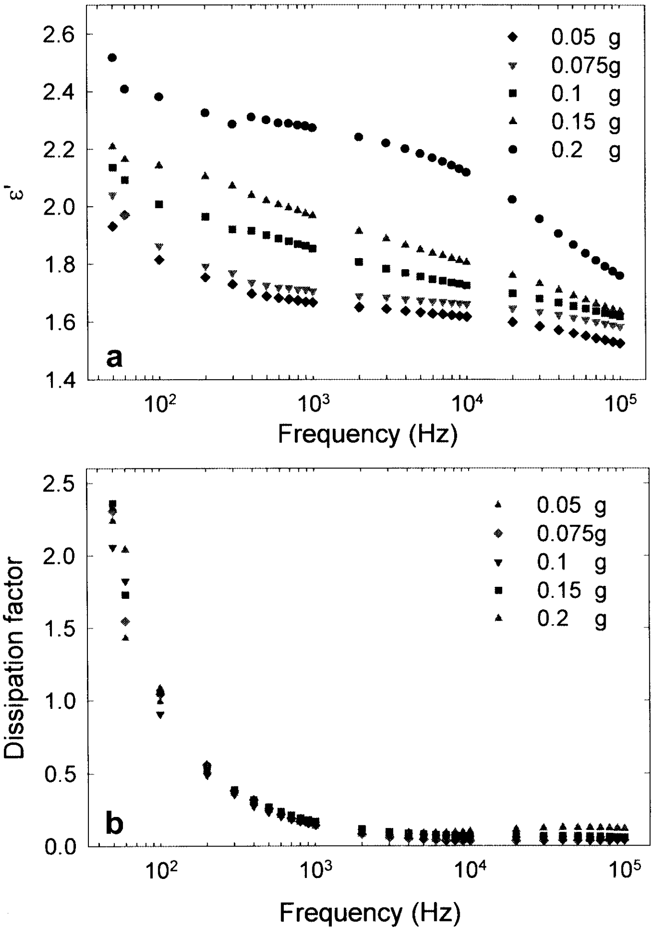

Fig. 5. Dielectric properties as a function of electric field frequency for 10 wt% various PPy-coated PE suspensions in mineral oil ($FeCl_3 \cdot 6H_20$ = 1.5 g): **a** dielectric constant and **b** dissipation factor

The linear regression lines in Fig. 4 show that the yield stress is fitted with E^2 when the amount of pyrrole is less than 0.075 g, consistent with the electrostatic polarization. At larger amounts of pyrrole, the yield stress is proportional to E^n, where $n < 2$. Actually the value of n decreases with the amount of pyrrole. This behavior arises from the increased conduction between the PPy-coated PE particles owing to the increased particle surface conductivity at large amounts of pyrrole. However, this phenomenon is different from the nonlinear conduction [23, 24] in that the increased conduction arises from the high particle surface conductivity, not from the field dissociation of the continuous phase [23, 24]. Even at a pyrrole content of 0.3 g, strands of coated particles shortcut the circuit in the electric fields and the ER experiments could not be performed.

The shear stress as a function of shear rate at $E = 1{,}000$ Vmm^{-1} and the suspension dielectric constant as a function of the electric field frequency are plotted in Fig. 6 for 10 wt% PPy-coated PE suspensions of various PPy-coated particles. The PPy-coated PE particles were synthesized by using 0.1 g pyrrole and various amounts of $FeCl_3 \cdot 6H_20$. The shear stresses are enhanced with the increase in the amount of $FeCl_3 \cdot 6H_20$ (Fig. 6a). The shear stresses increase with the amount of $FeCl_3 \cdot 6H_20$ because the PPy-coated PE particle polarization increases owing to the increased particle surface conductivity. The conductivities of the PPy-coated particles were measured as 1.60×10^{-9}, 2.12×10^{-9}, 2.36×10^{-9}, 2.76×10^{-9}, and 2.97×10^{-9} Scm^{-1} for 0.5, 0.75, 1.0, 1.5, and 2.0 g $FeCl_3 \cdot 6H_20$, respectively, increasing with the amount of $FeCl_3 \cdot 6H_20$. It was also reported that the PPy conductivity increased with the increase in the amount of $FeCl_3 \cdot 6H_20$ [25]. Therefore, the enhanced PPy-coated PE particle polarization by the increased surface conductivity leads to an increase in the ER response. The enhanced particle polarization with the increase in the amount of $FeCl_3 \cdot 6H_20$ is also confirmed by dielectric data (Fig. 6b). The dielectric constants of the PPy-coated PE suspensions increase with the increase in the

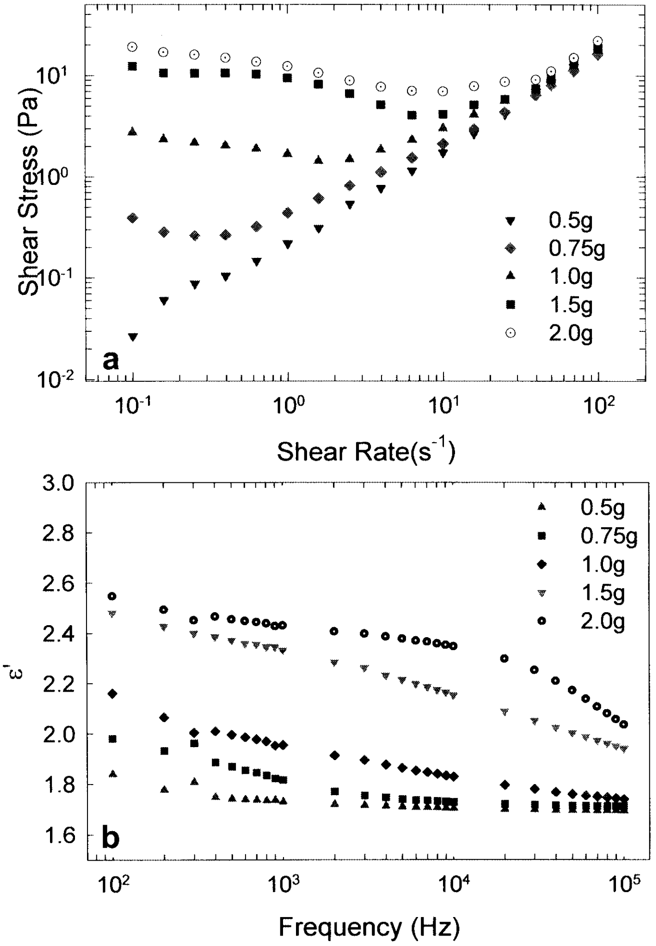

Fig. 6. **a** Shear stress as a function of shear rate at $E = 1{,}000$ Vmm^{-1} and **b** dielectric constant as a function of electric field strength for 10 wt% various PPy-coated PE suspensions in mineral oil (pyrrole = 1.0 g, *symbols*: amount of $FeCl_3 \cdot 6H_20$)

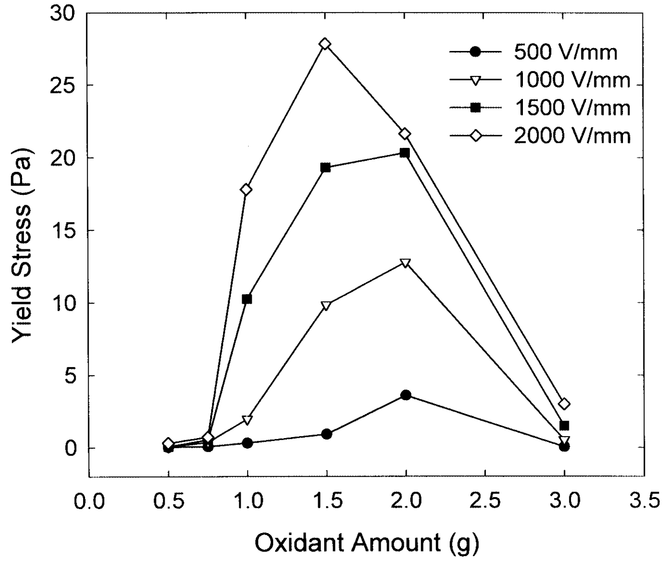

Fig. 7. Yield stress as a function of amount of $FeCl_3 \cdot 6H_20$ for 10 wt% various PPy-coated PE suspensions in mineral oil (pyrrole = 1.0 g)

amount of $FeCl_3 \cdot 6H_20$, suggesting that the enhanced particle polarization is due to the increase in the amount of $FeCl_3 \cdot 6H_20$, which leads to the enhanced ER response. However, it was observed that the ER response decreased rapidly when the amount of $FeCl_3 \cdot 6H_20$ was larger than a critical amount.

The dependence of the yield stress on the amount of $FeCl_3 \cdot 6H_20$ is presented in Fig. 7 for 10 wt% PPy-coated PE suspensions of various PPy-coated particles. The yield stress initially increases with the amount of $FeCl_3 \cdot 6H_20$, passes through a maximum, and then decreases with the amount of $FeCl_3 \cdot 6H_20$. The increase in the ER response with the amount of $FeCl_3 \cdot 6H_20$ is due to the enhanced particle polarization with the increased particle surface conductivity. The amount of $FeCl_3 \cdot 6H_20$ at the maximum seems to depend on the applied electric field strength, shifting to lower amounts at higher electric field strengths. The decrease in ER response at large amounts of $FeCl_3 \cdot 6H_20$ arises from the increased conduction between the PPy-coated PE particles. With the increase in the amount of $FeCl_3 \cdot 6H_20$, the particle surface conductivity of the PPy-coated PE particles increases, leading to the increased conduction. It is also notable that the yield stress is proportional to E^2 at lower amounts of $FeCl_3 \cdot 6H_20$ (less than 1.0 g), but the yield stress is proportional to E^n ($n < 2$) at higher amounts of $FeCl_3 \cdot 6H_20$ (higher than 1.5 g). Also, the value of n decreases with the increase in the amount of $FeCl_3 \cdot 6H_20$. As the conduction between the particles increases, the effective electric field between the particles decreases, leading to the decreased ER response. As a result, the ER response and the value of n decrease as the conduction between the particles increases.

The ER response decreases at high amounts of $FeCl_3 \cdot 6H_20$. The decreased ER response arises from the increased conduction between the particles, even though the particle polarization is still enhanced by the increased surface conductivity. Therefore, the ER response would not decrease even at high amounts of $FeCl_3 \cdot 6H_20$ if we restrict the increased conduction between the PPy-coated PE particles. For this purpose, we coated an insulating polymer on the PPy-coated PE particles ("double-coated" PE particles) and then measured the ER response of the corresponding suspension.

Double-coated PE particles were prepared by coating PVA on the PPy-coated PE particles (0.1 g pyrrole and 3.0 g $FeCl_3 \cdot 6H_20$), which showed the decreased ER response to be due to the increased conduction. PVA (2.0 g, Acros Chemical) was dissolved in 100 ml deionized water at 70 °C stirring with a magnetic stirrer. PPy-coated PE particles (2.0 g) were dispersed in the solution and stirred for 12 h. The double-coated PE particles were filtered

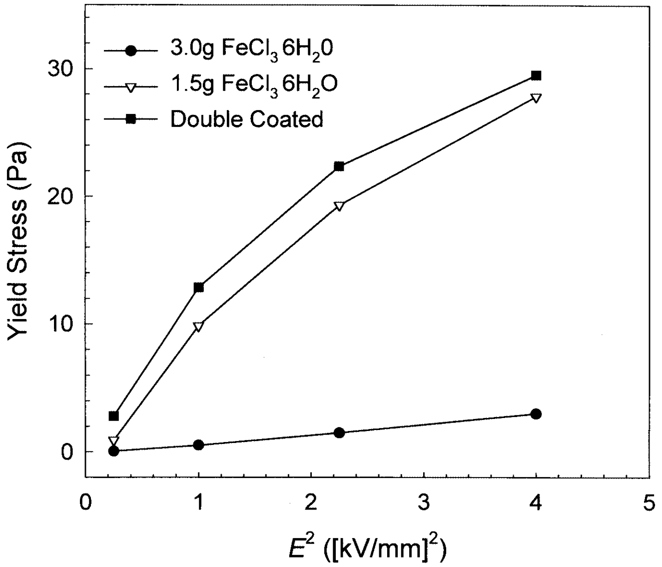

Fig. 8. Yield stress as a function of electric field squared for 10 wt% PPy-coated PE and double-coated PE suspensions in mineral oil (pyrrole = 1.0 g)

and washed several times with deionized water. The particles were dried in a vacuum oven at 50 °C for 24 h. The double-coated PE suspensions were prepared by dispersing the double-coated PE particles in mineral oil.

The dependence of the yield stress on the electric field squared is presented in Fig. 8 for 10 wt% PPy-coated PE suspensions and its double-coated PE suspension. For comparison, the ER response of the PPy-coated PE suspension of 1.5 g $FeCl_3{\cdot}6H_20$, which showed the most enhanced ER response with varying amount of $FeCl_3{\cdot}6H_20$, is included. As expected, the ER response of the double-coated PE suspension is greatly enhanced compared to that of the PPy-coated PE suspension of the 3.0 g $FeCl_3{\cdot}6H_20$. Even the ER response is higher than that of the PPy-coated PE suspension of the 1.5 g $FeCl_3{\cdot}6H_20$, confirming that the increased particle surface conductivity enhances the ER response if the increased conduction between the particles is restricted.

Conclusion

PPy-coated PE particles were prepared by the pyrrole polymerization on PE particles. PPy coating on the PE particles was observed by SEM. It was found that the ER response (yield stress and shear stress) increased with the coating of PPy on the PE particles. The ER response initially increases with the amount of pyrrole or $FeCl_3{\cdot}6H_20$, passes through a maximum, and then decreases with the amount of pyrrole or $FeCl_3{\cdot}6H_20$. The increase in the ER response with the amount of pyrrole or $FeCl_3{\cdot}6H_20$ is due to the enhanced particle polarization with the increased particle surface conductivity. The ER responses were consistent with the dielectric properties of the corresponding suspensions, suggesting that the enhanced ER response arose from the enhanced particle polarization due to the coating of PPy on PE particles. The decrease in the ER response at large amounts of pyrrole or $FeCl_3{\cdot}6H_20$ arises from the increased conduction between the PPy-coated PE particles. PVA was coated on the PPy-coated PE particles to restrict the increased conduction. It was found that the ER response was greatly enhanced by restricting the increased conduction.

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References

1. Winslow WM (1949) J Appl Phys 20:1137–1140
2. Deinega YF, Vinogradov GV (1984) Rheol Acta. 23:636–651
3. Shulman ZP, Gorodkin RG, Korobko EV (1981) J Non-Newt Fluid Mech 8:29–41
4. Gast AP, Zukoski CF (1989) Adv Colloid Interface Sci 30:153–202
5. Weiss KD, Carlson JD (1993) J Intell Syst Struct 4:13–34
6. Stangroom JE (1991) J Stat Phys 64:1059–1072
7. Klass DL, Martinek TW (1967) J Appl Phys 38:75–80
8. Klingenber DJ, Zukoski CF (1990) Langmuir 6:15–24
9. Klingenberg DJ, Dierking D, Zukoski F (1991) J Chem Soc Faraday Trans 87:425–430
10. Filisko FE, Razdilowski LH (1990) J Rheol 34:539–552
11. Otsubo Y, Sakine M, Katayama S (1992) J Colloid Interface Sci 150:324–330
12. Kim YD, Klingenberg DJ (1996) J Colloid Interface Sci 168:230–234
13. Kim YD (2001) J Colloid Interface Sci 236:225–232
14. Ikazaki F, Kawai A, Uchida K, Kawakami T, Edamura K, Sakurai K, Anzai H, Asako Y (1998) J Phys D Appl Phys 31:336–347
15. Otsubo Y, Edamura K (1994) J Colloid Interface Sci 168:230–234
16. Kim SG, Kim JW, Choi HJ, Suh MS, Shin MJ, Jhon MS (2000) Colloid Polym Sci 278:894–898
17. Cho MS, Choi HJ, To K (1998) Macromol Rapid Commun 19:271–273
18. Goodwin JW, Markham GM, Vincent B (1997) J Phys Chem B 101:1961–1967
19. Block H, Kelly JO, Qin A, Watson T (1990) Langmuir 6:6–14
20. Marshall L, Zukoski CF, Goodwin JW (1989) J Chem Soc Faraday Trans 85:2785–2795
21. Sprecher AF, Carlson JD, Conrad H (1987) Mater Sci Eng 95:187–197
22. Lascelles SF, Armes SP (1997) J Mater Chem 7:1339–1347
23. Foulc JN, Atten P, Felici N (1994) J Electrostat 33:103–112
24. Wu CW, Conrad H (1996) J Phys D Appl Phys 29:3147–3153
25. Bjorklund RB, Liedberg B (1986) J Chem Soc Chem Commun 1293–1295