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Rapid communication

Comment on "Preparation and electrorheological properties of triethanolamine-modified TiO_2"

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Abstract

Comments on the recent report of electrorheological (ER) properties of an organic modified titanium dioxide with considerably high yield stress are given based on the analysis of its yield stress data as a function of applied electric field strengths. Using our previously reported universal yield stress equation and critical electric field strengths deduced, it is found that we can collapse their data onto a single curve.

Keywords: Electrorheological fluid; Yield stress; Universal yield stress equation

1. Introduction

It is well known that the electrorheological (ER) fluid is a kind of fascinating materials which is composed of polarizable particles dispersed in insulating liquids and can change its state reversibly from liquid-like to solid-like phase with the aid of electric field [1–3]. Since these tunable ER properties have made ER fluids applicable for various electromechanical devices including clutch and shock absorbers [4], many studies are focusing on investigating the ER performance. Among the plenty of rheological parameters, the yield stress has attracted much attention due to its important role in both understanding ER characteristics and designing the ER devices [5]. In this comment, we replotted the yield stress reported by Cao et al. [6], and analyzed it with a universal equation by normalizing yield stress and the applied electric field strengths [7]. They found improved ER properties of an organic modified titanium dioxide with considerably high yield stress, which was attributed to the high molecular dielectric dipole moment of doping materials [6]. Furthermore, it can be also noted that more general universal classes of ER phenomena with a scaling behavior in the solid fraction has been studied with a semiclassical basis [8,9].

2. Yield stress

Among many models for ER fluids to explain the relationship between yield stress and ER behaviors studied, a good agreement between predicted and measured ER performances was observed based on either polarization or nonlinear conductivity model for the ER fluids. Here, a simple correlation between yield stress (τ_y) and applied electric field strength (E_0) is presented in a power law as follows [10–12],

$$\tau_y \propto E_o^m. \quad (1)$$

The yield stress at low E_0, predicted from the polarization model, is linearly proportional to the square of the electric field strength (E_0^2). However, the nonlinear conductivity effect becomes dominant in bulk conducting particle model and the power law index for yield-stress approaches to 3/2 at high E_0, implying that the electric response of the fluid becomes nonlinear, e.g., electrical breakdown or particle discharge at the high electric field strength occurs, as the gap between the conducting particles in the fluid decreases. Here, the ER effect is mainly caused by the liquid media induced conductivity enhancement among nearly touching

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particles. The conductivity mismatch rather than the dielectric constant mismatch between particles and liquid media was considered to be a dominant factor for the dc and low-frequency ac excitation [13]. Note that the conduction model takes into account the particle interaction only and does not consider the microstructural changes which occur after the imposition of an electric field.

3. Universal yield stress equation

To represent the yield stress data for a broad range of electric field strengths and to describe the deviation of the yield stress from the polarization model, Sim et al. [14] introduced the critical electric field strength, E_c, into their hybrid yield stress formula, which is represented as

$$\tau_y(E_o) = \alpha E_o^2 \left(\frac{\tanh \sqrt{E_o/E_c}}{\sqrt{E_o/E_c}} \right). \quad (2)$$

Here, α depends on the dielectric property of the fluid, the particle volume fraction, and $\beta = (\varepsilon_p - \varepsilon_c)/(\varepsilon_p + 2\varepsilon_c)$. ε_o is permittivity of free space, ε_c is dielectric constant of liquid media, and ε_p is dielectric constant of solid particle. By constructing E_o vs. τ_y plot (on log curve), E_c originated from nonlinear conductivity effect is obtained by the crossover point of the slopes for all ranges of the electric field strengths. The slope in E_o vs. τ_y plot is 3/2 for large E_o, while it approaches 2 for small E_o as shown in Eqs. (3) and (4). Eq. (2) has the following two asymptotic characteristics at low and high electric field strengths:

$$\tau_y = \alpha E_o^2 \quad \propto E_o^2 \text{ for } E_o \ll E_c\,. \quad (3)$$

On the other hand,

$$\tau_y = \alpha \sqrt{E_c} E_o^{3/2} \quad \propto E_o^{3/2} \text{ for } E_o \gg E_c\,. \quad (4)$$

Eqs. (3) and (4) indicate that τ_y is proportional to E_o^2 at low E_o as expected from the polarization model and to $E_o^{3/2}$ at high E_o as predicted from the conductivity model. Here, we reanalyzed the original Figs. 3 and 4(a) reported in Ref. [6] and then plotted the yield stresses as a function of applied electric field strengths in a log-log scale, and obtained the E_{cs} which resulted from the crossover of two slopes, corresponding to the polarization model (slope = 2) and conductivity model (slope = 1.5), respectively as shown in Fig. 1. The E_{cs} are deduced to be 0.9450 kV/mm for the ER fluid tested under DC electric field, 1.0670 and 1.09139 kV/mm tested under AC electric field with 20 and 200 Hz, respectively. Cao et al. [6] interpreted the difference in yield stress by analyzing the dielectric properties of the ER suspensions.

A universal equation (Eq. (5)), normalized with E_c and $\tau_y(E_c) = \alpha E_c^2 \tanh(1) = 0.762\,\alpha E_c^2$, is used to collapse all the data onto a single curve.

$$\hat{\tau} = 1.313 \hat{E}^{3/2} \tanh \sqrt{\hat{E}}, \quad (5)$$

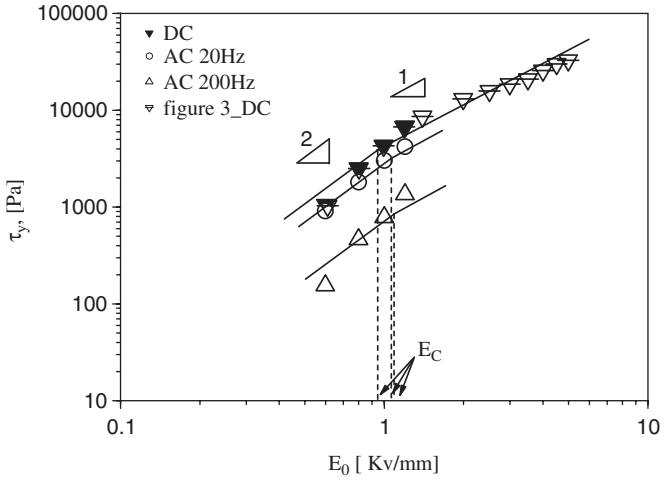

Fig. 1. Replotted yield stress versus electric field strengths for triethanolamine-modified TiO_2 based on ER fluid under DC and an AC electric fields with two different frequencies along with data from Fig. 3 of Ref. [6].

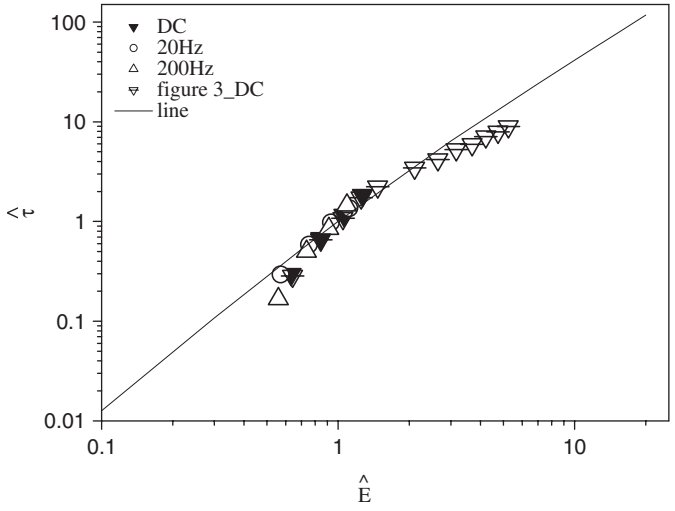

Fig. 2. $\hat{\tau}$ versus $\hat{E}$ for triethanolamine-modified TiO_2 based on ER fluid under DC and AC electric field with two different frequencies. The solid line is drawn with Eq. (5).

where $\hat{E} \equiv E_o/E_c$ and $\hat{\tau} \equiv \tau_y(E_o)/\tau_y(E_c)$. The E_c gives the criteria for selecting low and high electric field strengths in the normalized scaling function. Although various ER fluids [15–18] have been found to follow this universal yield equation, E_c is not a universal quantity and depends on the system properties. The data represented in Fig. 2 which was taken from Figs. 3 and 4(a) of Ref. [6], are observed to collapse onto a single curve by using our universal yield stress equation of Eq. (5) with a slight deviation from the solid line.

To better fit experimental data, a modified universal correlation introducing an additional parameter b was suggested for the systems that are partly discord with Eq. (5) while the plots seem to follow an alternative curve [7]. We rescaled $\hat{\tau}$ with $\hat{\hat{\tau}} = \hat{\tau}\hat{E}^{4b}$ and $\hat{E}$ with $\hat{\hat{E}} = \hat{E}^{1+2b}$ for

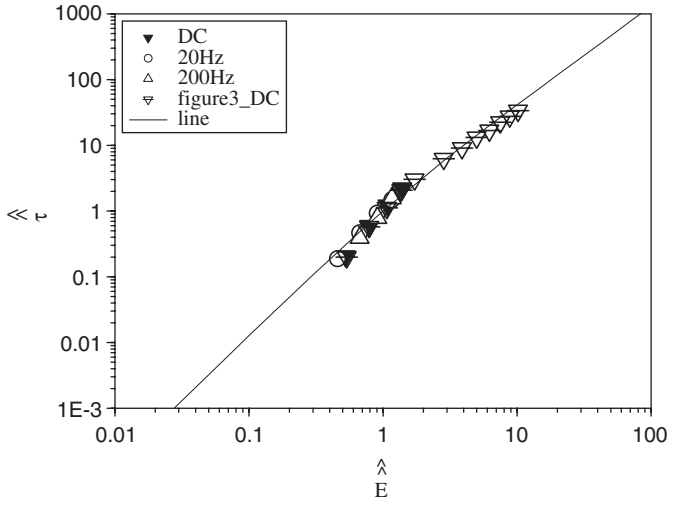

Fig. 3. Plot of $\hat{\tau}$ versus $\hat{E}$ for triethanolamine-modified TiO_2 based on ER fluid under DC and AC electric field with two different frequencies. The solid line is drawn with Eq. (6).

the data, and derived a new equation as

$$\hat{\tau} = 1.313\hat{E}^{3/2} \tanh\sqrt{\hat{E}} \tag{6}$$

for a universal curve. From Fig. 3 we were able to confirm that the points $(\hat{\tau}, \hat{E})$, which were recalculated with $b = 0.20$, were located along the curve of Eq. (6) with smaller deviations than the points $(\hat{\tau}, \hat{E})$ along the curve of Eq. (5) in Fig. 2. Therefore, Eq. (6) is believed to be very useful in constructing the master curve for ER fluids. In addition, note that the deviation of the E_c do not change the scaled universal yield stress equation itself but the point moves following the universal yield stress equation, moving up for the higher E_c and moving down for the lower E_c [19].

In summary, Figs. 1–3 in this comment clearly demonstrates the universal scaling behavior of the yield stress for the experimental data obtained from Ref. [6].

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