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The electrorheological effect for polyhedral silsesquioxane cage structures with cyanopropyl functional groups

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ABSTRACT

Previous research has shown that sulfonated polyhedral silsesquioxane (s-POSS) material when mixed with silicone oil (PDMS) exhibits a significant ER effect. For the first time here we show that cyanopropyl POSS (c-POSS) particles in silicone oil also show significant ER activity. The yield stress, τ_y, scales with the electric field, E, as $\tau_y \propto E$. The elastic storage modulus of the suspension at small strains ($\gamma = 0.10$) scales with the electric field E as $G' \propto E^{0.99-1.76}$.

1. Introduction

The electrorheological effect causes the viscosity of a suspension to increase up to four orders of magnitude by applying an electric field. The increase in viscosity is caused by the alignment of the particles into more complex structures within the suspension [1]. Because this alignment process can be controlled using the electric field, electrorheological fluids represent a class of materials that possess tunable viscosities; the viscosity of the fluid changes depending on the magnitude, frequency, and procedure of the applied electric field [2,10]. The behavior seen with ER fluids is similar to the behavior seen with solid ER materials such as ER gels and elastomers. The electric field control of ER fluids has found many uses and applications in both devices and processes [3].

Typical ER fluids use solid polarizable particles within a non-conducting liquid. Most research for improving the ER effect has focused on the solid phase of the ER fluid. Typically the most popular solid phase materials have been ferroelectric materials (e.g. Barium Titanate) [4], ceramic materials (e.g. silica, titania) [5] and polymeric materials (e.g. Polyaniline) [6]. Additionally nanomaterials have been investigated as well. There has been some research focused on the effects caused by the selection of the liquid [7,8].

Recent work has demonstrated that functionalized silsesquioxanes can be used as a solid phase material in ER fluids [9]. POSS (polyhedral oligomeric silsesquioxane) molecules are known to be great nano building blocks. POSS molecules have a highly symmetrical, three dimensional, cage like structures composed of silicon and oxygen. Due to the highly organized base structure of POSS it is possible to add functional groups, both organic and inorganic, with precision. Furthermore it was shown that the ER effect of this class of materials is determined by the type of groups attached to the nanocage structure [9]. While the ER effect has been seen in sulfonate POSS suspensions to date no other silsesquioxane materials have been published that demonstrated similar effects.

This paper demonstrates a new ER fluid based upon cyanogroups attached to the polyhedral nanocage structure. It should also be noted that c-POSS marks the first closed cage ER structure to our knowledge with just a single functional group attached that demonstrates a strong ER effect. Previous research has already shown that octaisobutyl POSS, another closed cage structure, does not give an ER effect [9]. In addition to demonstrating the ER effect for these new ER materials, this paper seeks to answer how changing the concentration of solid cyanopropylisobutyl POSS ($C_{32}H_{69}NO_{12}Si_8$) nanocages in a PDMS oil will affect the viscoelastic and rheological behavior of the suspension. The magnitudes of the shear modulus, G' (storage modulus) and G'' (loss modulus), and the static and dynamic yield stresses of the c-POSS ER fluids will be analyzed. In this letter we focus on the effects of the electric field and particle concentrations for this new c-POSS ER fluid.

2. Methods and materials

The cyanopropylisobutyl POSS nanoparticles ($\rho = 1.16$ g/cm^3)

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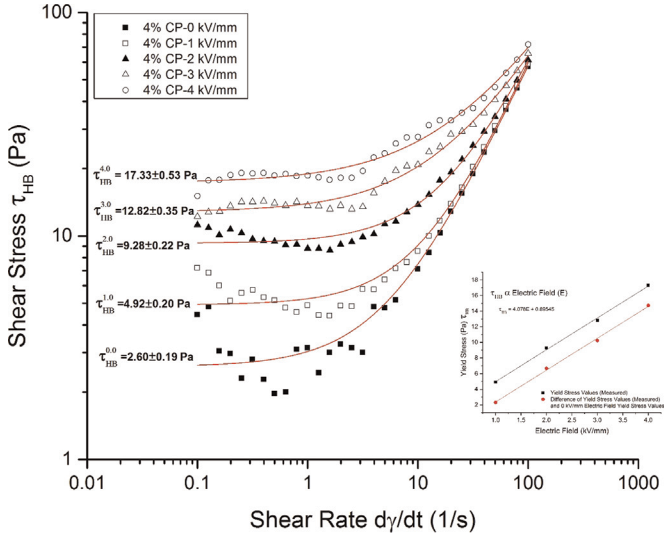

Fig. 1. Shear stress vs. strain rate for 4 wt% c-POSS ER fluid.

were purchased from Hybrid Plastics and the 0.485 Pa s (500 cSt) PDMS oil was purchased from Sigma-Aldrich. This experiment included the preparation of six suspension samples of varied concentrations. These prepared samples contained concentrations of 2, 4, 8, 10, 15, and 20 wt%. (1.68%, 3.37%, 6.78%, 8.50%, 12.86%, and 17.29% c-POSS volume/total volume) cyanopropylisobutyl POSS nanoparticles in 0.485 Pa s (500 cSt) PDMS oil. Before beginning testing on the rheological behavior of the prepared suspensions the nanoparticles and the PDMS oil were dried for 24 h using a Napco (model 5831) vacuum oven. The dried cyanopropylisobutyl POSS was then ground to a fine powder (50–500 nm) using a mortar and pestle [See Supporting Electronic Supplementary material for SEM images]. Suspension samples were then prepared using an Adventurer-Ohaus balance. To ensure complete dispersion and prevent agglomeration of the cyanopropylisobutyl POSS nanoparticles throughout the PDMS oil a Buehler LTD, Ultramet III Sonic Cleaner was used to agitate each sample for two hours before testing.

Once all six suspensions were prepared, they were individually tested using a rate controlled Anton Paar MCR 302 Rheometer. A

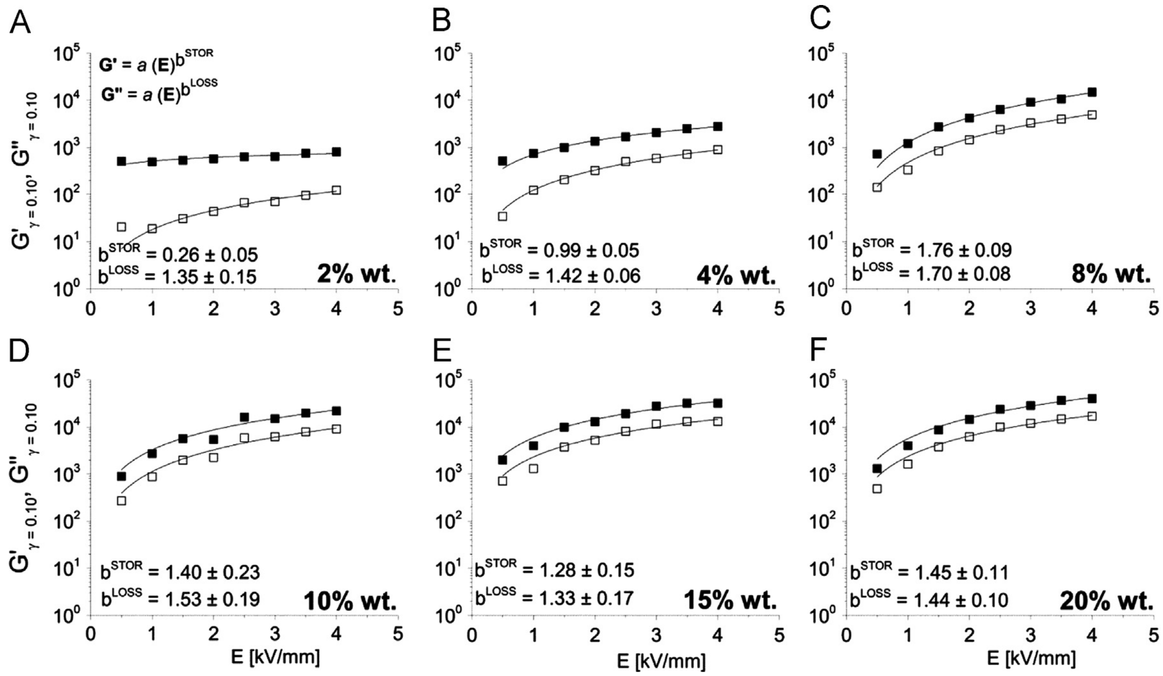

Fig. 2. *G*′(closed) and *G*″(open) at strain = 0.10% for different electric fields for A–F concentration increases from 2 to 20 wt%.

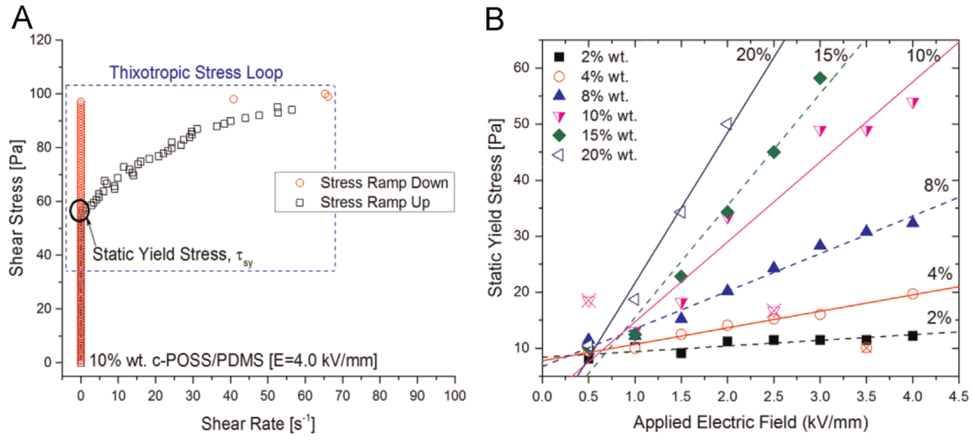

Fig. 3. (A) Thixotropic stress loop for 10% c-POSS/PDMS at 4.0 kV/mm. (B) Static yield stress vs. electric field for c-POSS ER fluids (*Note*: data in Fig. 3B contains 3 outlier points not included in linear fits).