Electrorheological fluid under elongation, compression, and shearing

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Electrorheological (ER) fluid based on zeolite and silicone oil under elongation, compression, and shearing was investigated at room temperature. Dc electric fields were applied on the ER fluid when elongation and compression were carried out on a self-constructed test system. The shear yield stress, presenting the macroscopic interactions of particles in the ER fluid along the direction of shearing and perpendicular to the direction of the electric field, was also obtained by a HAAKE RV20 rheometer. The tensile yield stress, presenting the macroscopic interactions of particles in the ER fluid along the direction of the electric field, was achieved as the peak value in the elongating curve with an elongating yield strain of 0.15–0.20. A shear yield angle of about 15°–18.5° reasonably connected tensile yield stress with shear yield stress, agreeing with the shear yield angle tested well by other researchers. The compressing tests showed that the ER fluid has a high compressive modulus under a small compressive strain lower than 0.1. The compressive stress has an exponential relationship with the compressive strain when it is higher than 0.1, and it is much higher than shear yield stress.

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I. INTRODUCTION

Electrorheological fluids are intelligent materials having attracted much interest in the recent decades for their wide industrial application potential. Most of the earlier research has concentrated on the shear behavior of ER fluids. Applications based on ER fluids, such as couplings, clutches, dampers, employ the shear strength of ER fluids under external electric field [1]. So among the properties of ER fluids, shear yield stress and the ratio of shear yield stress to zero-field viscosity of ER fluids are the most important parameters for applications. To obtain the same output force of ER actuators, a higher shear yield stress means a smaller actuator. The ratio determines the adjusting range of the output force. Researchers have made great efforts to improve the two values. In a recent report by Kawakami *et al.* [2], the shear yield stress was 5.08 kPa under a 4 kV/mm dc electric field, and the ratio of shear yield stress to zero-field viscosity had been developed to 2.9×10^4. Zhang reported a shear yield stress of 8 kPa under a 2.4 kV/mm dc electric field [3]. We have reported a shear yield stress of 26 kPa under a 5 kV/mm dc electric field [4]. Also there are several other reports of ER fluids with high shear strength [5]. However, in most reports, the shear yield stress of ER fluids is lower than 5 kPa. The low shear strength of ER fluids is recognized as the bottleneck of the applications utilizing ER fluids. In recent years, besides the further development of the shear strength of ER fluids, researchers began to explore other ways of utilizing ER fluids that may provide a higher force performance than shearing. Squeezing ER fluids is such a method. The squeezing strength of ER fluids was found to be much higher than its shear strength, which was usually explained by the structural strength of ER fluids. The squeezing strength was also found largely depending on the frequency and amplitude of the oscillatory squeezing excitation [6,7]. Applications depending on this squeeze effect had been constructed too [6]. However, when oscillatory squeeze excitation of ER fluids was applied in a damper, the squeeze speed of ER fluids was not constant, and elongation of ER fluids was also observed. Thus the experimental results gave the result of both elongation and compression of ER fluids rather than the compressive strength only.

On the other hand, ER fluids are usually introduced as materials that change instantly from a liquid state to a solid state under the application of an electric field. The structure and the mechanical properties of this special solid can be investigated. Tao and co-workers have done much work on the arrangement of particles in ER fluids [8–11]. Lukkarinen and Kaski have performed simulations of ER fluids under shear, compression, and elongation where the effect of the body centered tetragonal (BCT) structure is presented [12]. However, few people have done experiments to test the quasistatic compressive and tensile property of ER fluids as solids. Investigating the properties of ER fluids dealt as solid under slow compression and elongation is helpful for comprehending the ER effect. Thus the individual investigation of the elongating and compressing process of ER fluids is interesting for both academic researchers and engineers. In this paper, experimental investigation of the slow elongation and compression of an ER fluid based on zeolite and silicone oil under dc electric fields has been carried out and the test results are compared with the shear yield stress of the ER fluid.

II. EXPERIMENT

The schematic of the elongation and compression test system is shown in Fig. 1. The elongation and compression of ER fluids are done by a self-constructed computer-controlled moving plate. The maximum driving force of the working axle is 1000 N. The compression and elongation of the ER fluid were carried out between two parallel plates with dimensions of $32\times32\ \text{mm}^2$ and $35\times70\ \text{mm}^2$, respectively. The smaller plate with an area of $S=10.24\ \text{cm}^2$ is the upper plate. It is tightly connected to a force sensor fixed on the rigid beam of the working plate. The lower plate is fixed in an insulating trough that can hold ER fluids and move with the working axle. The upper plate is connected to the cathode

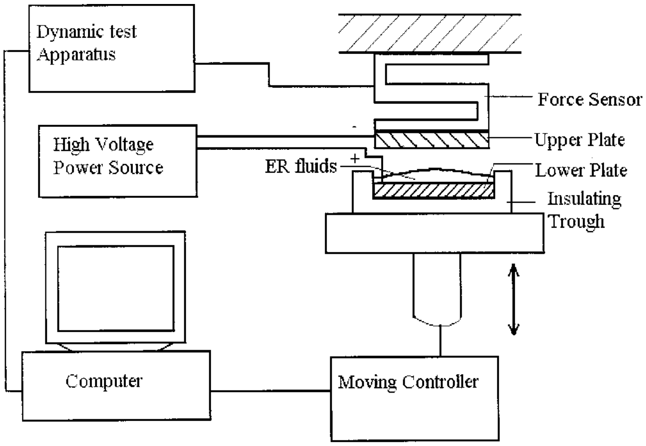

FIG. 1. Sketch of the elongation and compression test system.

while the lower plate is connected to the anode. The measuring range of the force sensor is ±49 N. The output signals of the force sensor are modulated by a dynamic test apparatus (DH-5935) and then sampled by the computer.

The ER fluid used in these experiments is based on zeolite and silicone oil. The preparing process and the characteristics of the ER fluid were reported in a former paper [4]. The ER fluid used in the experiments is the same. It has a particle weight concentration of 43%.

In the elongating experiment, the original gap between the two parallel plates is set as 1 mm, then the lower plate moves down by 3 mm under the controlling of the computer to elongate the ER fluid filling between the two plates. In the compressing experiment, the original gap is set as 2 mm, then the lower plate moves up by 1.5 mm to compress the ER fluid. The electric field is applied on the ER fluid before the moving of the lower plate and is turned off right after the lower plate stops moving. The moving speed of the lower plate is uniform, $\nu = 0.4167$ mm/s. This slow test can be called a quasistatic test. The elastic factor of the force sensor is $K = 0.014\,08$ mm/N. The trough is made of polytetrafluroethylene with a elastic modulus on the scale of 1 GPa. The distortion of the insulating trough under a pressure of 100 kPa is only about 1 μm and can be neglected in this experiment. If the force applied on the upper plate is F and S is the area of the upper plate, then the tensile stress or the compressive stress can be presented as

$$\tau = F/S. \tag{1}$$

The tensile strain or compressive strain γ can be presented as

$$\gamma = \frac{1}{h_0}\left(\nu t - \frac{F}{K}\right), \tag{2}$$

where h_0 is the original gap between the two parallel plates and t is the moving time of the lower plate.

The shear stress of the ER fluid versus electric field was measured by a HAAKE RV 20 rheometer with a rotation plate with an outer diameter of 20 mm. The shear yield stress of the ER fluid τ_E was obtained by fitting the shearing curve to Bingham model. All the experiments were done at room temperature (22 °C).

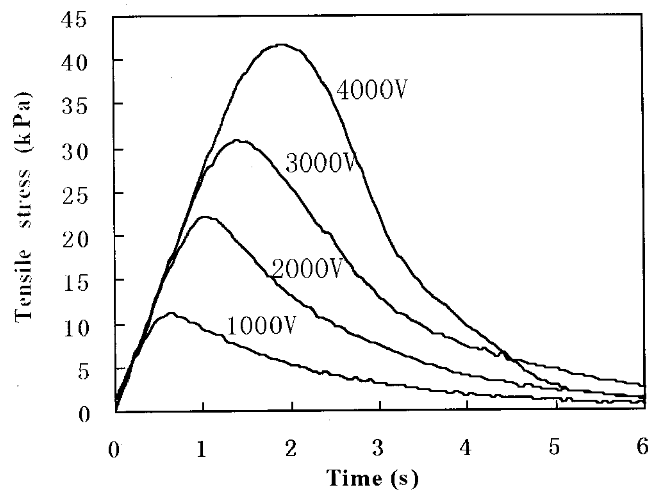

FIG. 2. Tensile stress vs time.

III. RESULTS AND DISCUSSIONS

In the test of elongating the ER fluid along the direction of the applied dc electric field, the tested tensile stress presented the interaction strength of particles along the field direction. The tensile stress versus time is shown in Fig. 2. The tensile stress versus tensile strain is shown in Fig. 3. The two figures show that the elongation of the ER fluid can be divided into three processes. In the first process, tensile stress increased almost linearly with time and tensile strain. The tensile strain is no more than 0.05 in this process. This process can be called an elastic process. In the second process, tensile stress increased slowly to a peak value while tensile strain increased much quicker than that in the first process. The peak value is taken as tensile yield stress τ_{elg} of the ER fluid. It presents the highest interaction of particles in the ER

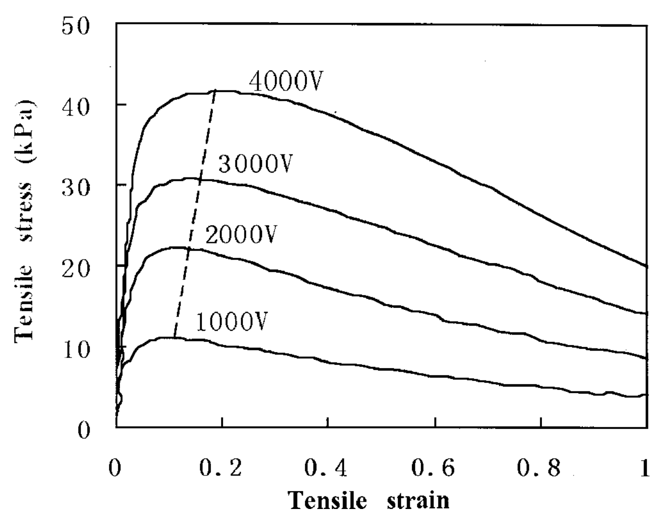

FIG. 3. Tensile stress vs tensile strain.

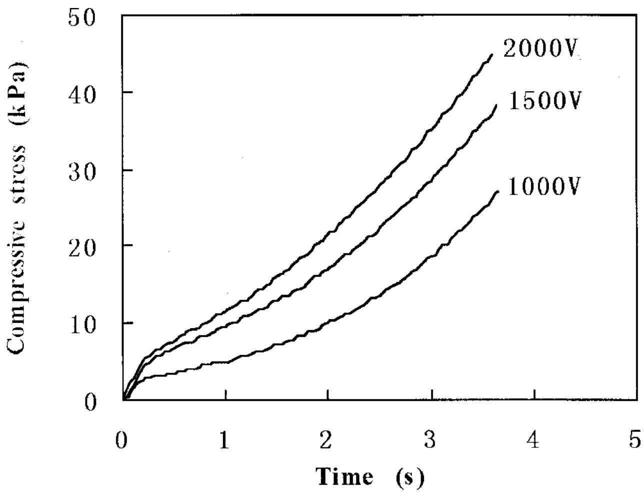

FIG. 4. Compressive stress vs time.

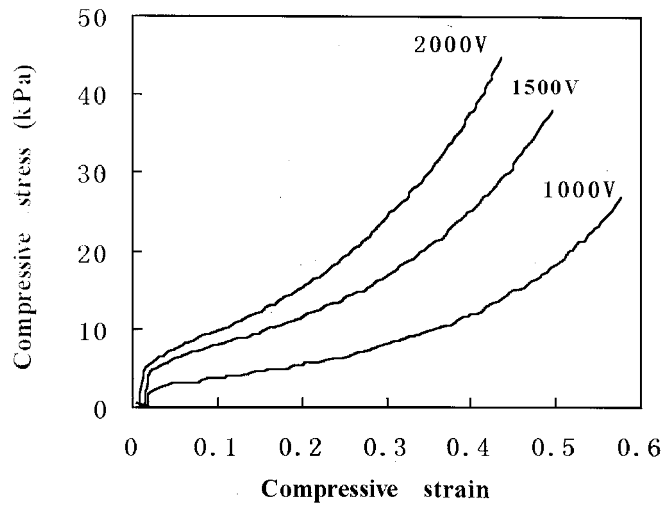

FIG. 5. Compressive stress vs compressive strain.

fluid along the direction of the applied dc field. Tensile strain is no more than 0.2 in this process. The tensile yield strain corresponding to the tensile yield stress slightly increased with the applied field strength as the dashed line shown in Fig. 3. When a 1000 V dc field was applied on the ER fluid, a tensile yield stress of 11 kPa was obtained at a tensile yield strain of 0.11. When a 4000 V dc field was applied on the ER fluid, a tensile yield stress of 42 kPa was obtained at a tensile yield strain of about 0.2. The tested tensile yield stress is proportional to the external voltage with an exponent of 1.2. This process can be called a yield process. After the yield process, tensile stress decreased slowly to zero and tensile strain increased quickly. It can be called a post yield process or sticking process. In this process, the ER fluid was departing from the upper plate and not filling the gap between the two plates anymore, so it is not as important for research as the former two processes.

In the test of compressing ER fluid along the direction of the applied dc field, the tested compressive stress presented the resistance of the ER fluid under compression. Compressive stress of the ER fluids versus time is shown in Fig. 4. Compressive stress versus compressive strain is shown in Fig. 5. The compressive modulus G can be calculated from the following equation:

$$G=\frac{\Delta\tau}{\Delta\gamma}. \tag{3}$$

$\Delta\tau$ is the compressive stress change corresponding to a small compressive strain change of $\Delta\gamma$. G is the compressive modulus for this small change of compressive strain at a certain compressive strain. Compressive modulus versus compressive strain is shown in Fig. 6.

Figures 4–6 show that the compression of the ER fluid can be divided into two processes. During the first process, the compressive stress increased quickly with the increase of the compressive strain, but the compressive modulus decreased quickly from a high value to the lowest value. When a 2000 V dc field was applied on the ER fluid, the compressive modulus was as high as 200 kPa at a compressive strain of 0.015 and then decreased to 46 kPa at a compressive strain of 0.1. The decrease of the compressive modulus showed that the ER fluid was very stiff at small strains. In the second process, the compressive strain is higher than 0.1. Compressive stress and compressive modulus both increased with the increase of compressive strain. The fitted curves of compressive stress and compressive modulus versus compressive strain in this process are shown in Figs. 7 and 8, respectively. The compressive stress and the compressive modulus can be described by exponential functions of compressive strain. The fitted equations are shown in the two figures too. When the applied dc field increased, the factor that multiplies the exponent item also increased. Thus a high field means a high compressive stress and a high compressive modulus. In the compressing tests, the voltages are held constant. The applied electric field increased while the gap between the two plates decreased. This strengthened the ER effect and the compressive stress of the fluid. If the effect of increasing electric field is removed during the compressing process, the electric field is kept constant, a less dramatic

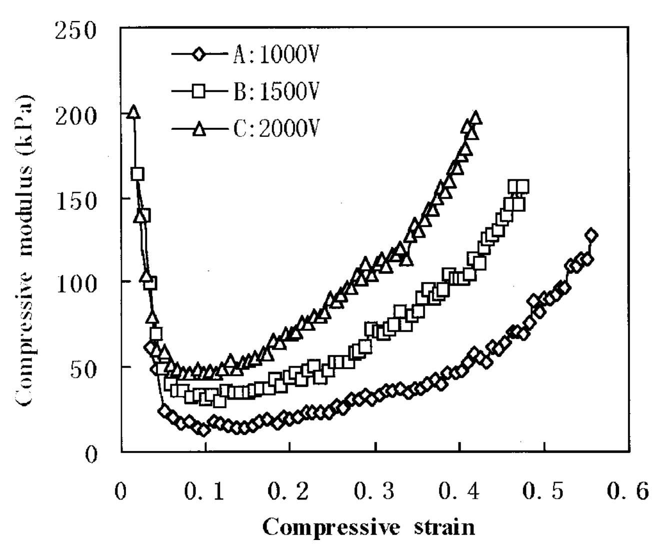

FIG. 6. Compressive modulus vs compressive strain.

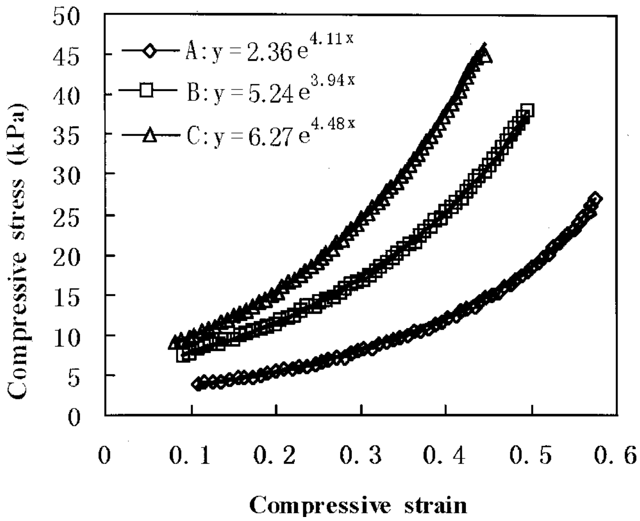

FIG. 7. Experimental and fitted compressive stress vs compressive strain.

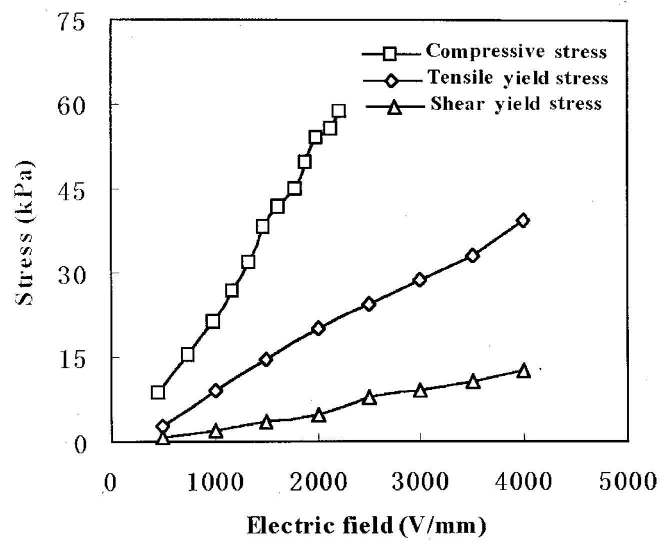

FIG. 9. Stress values of the ER fluid.

increase in compressive stress with compressive stain would likely be obtained. This also means that a less dramatic increase in compressive modulus with compressive strain would be obtained. However, the physical meaning of the exponential relationship between the compressive strain and the compressive stress or the compressive modulus is not clear yet.

The shear yield stress of the ER fluid tested by the HAAKE RV20 rheometer is shown in Fig. 9. The shear yield stress is proportional to the external electric field with an exponent of 1.35. It reasonably agrees with the reports of other researchers [13]. The tensile yield stresses and compressive stresses are also shown in Fig. 9. The compressive stresses were the maximum stresses during the compressing process, which were taken from the end points of the tested compressing curves. The tensile yield stresses were taken from the peak values of the tested elongating curves.

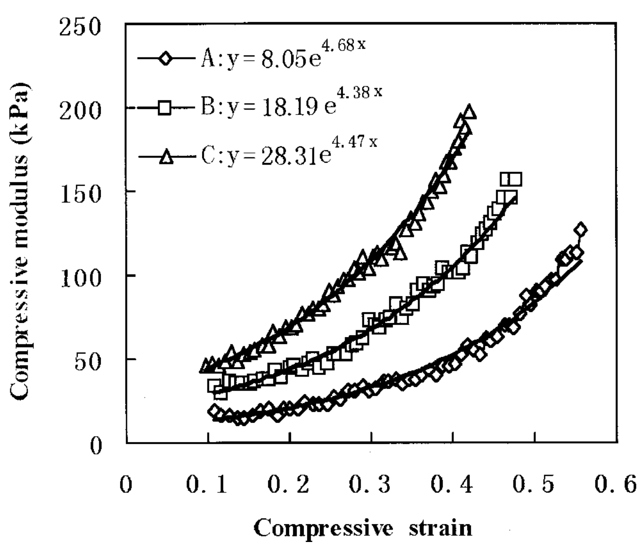

FIG. 8. Experimental and fitted compressive modulus vs compressive strain.

In the theoretical analysis calculating shear yield stress of ER fluids, the interaction between particles along the shearing direction f_s is calculated from the interactions between particles along the field direction f_0 [14,15]. The shear yield stress is proportional to the attraction forces between particles [16]. The interaction between two particles along the direction of shearing is obtained by multiplying the sine of the shear yield angle θ as described by Eq. (4),

$$f_s = f_0 \sin\theta. \tag{4}$$

Usually $\theta = \arctan\gamma$, γ is the shear yield stain of ER fluids.

To verify the above relationship, researchers have tried to measure the attraction force between two spheres [17] or half spheres [18]. But to measure the attraction force between spheres in a millimeter scale is very hard. In these experiments, the dimensions of the tested spheres are usually in a micrometer scale, much larger than the real particles. However, shear yield stress τ_E presents the macroscopic interactions of particles in ER fluids along the shear direction, tensile yield stress τ_{elg} presents the macroscopic interactions of particles in ER fluids along the field direction. The shear direction is usually perpendicular to the direction of the applied field. If the microscopic presentation of forces between two particles as Eq. (4) showed is right, then the relationship between shear yield stress τ_E and tensile yield stress τ_{elg} can be described by the following equation:

$$\tau_E = \tau_{\mathrm{elg}} \sin\theta. \tag{5}$$

According to the tested shear yield stresses, tensile yield stresses and the relationship presented by Eq. (5), shear yield angle can be calculated to be in the range of 15°–18.5°. This result agrees with the experimental report by Wu *et al.* of a shear yield strain of $\gamma = 0.3$ and a yield angle of 16.7° very well [15]. Thus shear yield stress and tensile yield stress of ER fluids have a good quantitative relationship by employing a parameter of shear yield angle. This experiment verified the relationship of the interactions between particles along the applied field direction and along the shearing direction in macroscope.

During the compressing process, the gap between particles decreased. This had an effect of particle condensation. Thus the particle volume fraction of the ER fluid increased and the structure of particles was more compact. So compressive stress is different from tensile yield stress or shear yield stress, which has no such condensation effect. However Fig. 9 shows that the compressive stress is much higher than the shear yield stress and the tensile yield stress of the ER fluid under the same dc electric field. The compressive stress is about ten times of the shear yield stress and two to three times of the tensile yield stress.

Different from the normal applications utilizing the shear strength or squeeze strength of ER fluids, the tensile stress of ER fluids can also be used. And according to the tested curves shown above, the applications can be more accurately designed.

IV. CONCLUSION

Experimental study of ER fluids based on zeolite and silicone oil under elongation, compression, and shearing has been carried out. The elongation and compression processes of ER fluids are presented. The tensile yield stress is about three to four times of shear yield stress. According to the macroscopic relationship between interactions of particles along the direction of the applied field and along the shearing direction, a shear yield angle of about 15°–18.5° has been obtained and it agrees with the reports of other researchers well. In the compressing process, the ER fluid is very stiff at small compressive stains, lower than 0.1. The compressive modulus decreases to the lowest value at a compressive strain of about 0.1. And then the compressive stress and the compressive modulus showed an exponential relationship with the compressive strain while the strain is higher than 0.1. The compressive stress is much higher than the tensile yield stress and the shear yield stress of the ER fluid under the same dc electric field.

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