Compressions of electrorheological fluids under different initial gap distances

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(Received 26 December 2002; revised manuscript received 3 March 2003; published 14 May 2003)

Compressions of electrorheological (ER) fluids have been carried out under different initial gap distances and different applied voltages. The nominal yield stresses of the compressed ER fluid under different conditions, according to the mechanics of compressing continuous fluids considering the yield stress of the plastic fluid, have been calculated. Curves of nominal yield stress under different applied voltages at an initial gap distance of 4 mm overlapped well and were shown to be proportional to the square of the external electric field and agree well with the traditional description. With the decrease of the initial gap distance, the difference between the nominal yield stress curves increased. The gap distance effect on the compression of ER fluids could not be explained by the traditional description based on the Bingham model and the continuous media theory. An explanation based on the mechanics of particle chain is proposed to describe the gap distance effect on the compression of ER fluids.

DOI: 10.1103/PhysRevE.67.051501 PACS number(s): 83.80.Gv, 83.60.Np, 83.60.La

I. INTRODUCTION

Electrorheological (ER) fluids have been widely investigated for their potential industrial applications such as clutches, dampers, engine mounts, and step actuators, etc. [1]. Because most of the applications are based on shear yield stress of ER fluids, a great deal of theoretical and experimental research has been concentrated on particle interactions to approach the shear yield stress [2]. However, the reported shear yield stress of ER fluids is usually lower than 10 kPa, and not high enough for many real applications. To design ER actuators with higher force performance, tensile and compressive behaviors of ER fluids have been investigated during recent years. The tensile stress and compressive stress of ER fluids have been found to be much higher than the shear yield stress [3]. Monkman has investigated the electrorheological effect under compression [4]. Vieira *et al.* have tested the tensile, compression and oscillatory squeeze, behaviors of an ER fluid based on carbonaceous particles and silicone oil [5]. Gong and Lim have experimentally determined the tensile and compression properties of ER fluids added with glass fiber [6]. Lee and co-workers have studied ER suspensions composed of silica particles and silicone oil under squeeze flow by changing applied electric field, particulate volume fraction, viscosity of host oil, and water content in particles [7]. Noresson and Ohlson have reported a critical study of the Bingham model in squeeze-flow mode, showing that the amplitude and frequency dependence is not well predicted by the Bingham model [8]. Recently we have compared compressing, elongating and shearing, behaviors of ER fluids [9], and have studied stepwise compressions of ER fluids under different constant voltages [10].

There are fewer theoretical works on compressive behavior of ER fluids when compared to experimental studies. Yang has described the tensile and compressive behaviors of dilute ER fluids by the electrostatic polarization model and Hertzian contact theory [11]. Lukkarinen and Kaski have simulated the mechanical properties using point-dipole model [12]. Besides the simulations, the compressive behaviors of ER fluids have often been considered a transformed shear behavior that predicts the compressive stress from the dimension of compressive flow, and the shear stress of ER fluids under the compression [13]. The radial velocity, radial pressure gradient, and the pressure acted on the plates when ER fluids are compressed between two parallel plates, have been given by Williams *et al.* [14]. When the compressing speed is very low, neglecting the viscous force, the ER fluids can be dealt with as a plastic fluid. The equation describing compressive stress P deduced from the report by Gartling and Phan-Thien [15] is

$$P=\frac{D}{3h}\tau_0, \tag{1}$$

where D is the diameter of the plate, h is the instantaneous distance between the plates, τ_0 is the yield stress of the plastic fluid. For ER fluids under external fields, it can be described by the Bingham model employing a yield stress τ_0. The equation shows that the compressive stress is not only proportional to the yield stress of the fluid, but also is affected by the structure parameter D/h.

For the high mechanical performance of compressive flow, application prototypes have been constructed based on the Bingham model and the continuous media theory, such as squeezing damper [8], engine mounts [14], and clutch incorporating compressive effect [16]. However, this continuous media theory is not always applicable. For instance, the experiments done by Vieira *et al.* at a low compressive speed of 0.5 mm/min showed that the compressive stress under a constant external electric field of 0.5 kV/mm and an initial gap distance of 2 mm, remained approximately constant in the compressive strain range of 0.1–0.5, independent of the structure parameters D/h [5]. This is obviously different from the description by Eq. (1). Also, a critical study of the Bingham model in a squeeze-flow mode has been reported by Noresson and Ohlson [8]. They found that the Bingham parameters tested from shear-flow mode are not valid for the calculation of the squeeze-flow mode behavior, and even the Bingham parameters directly obtained from squeeze-flow mode are valid for one amplitude and one frequency only.

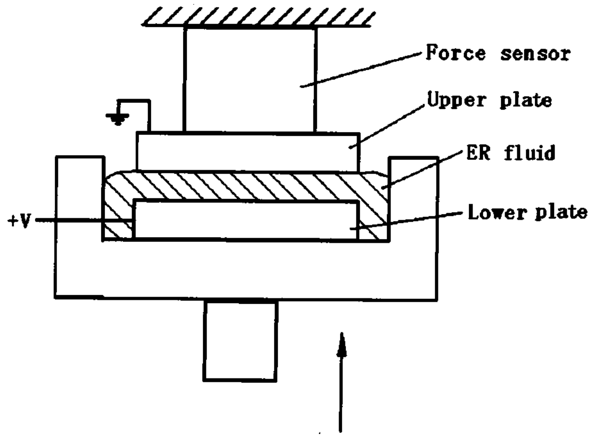

FIG. 1. Schematic of the experiment apparatus.

The step compressions done by us have found deviations from the traditional description at strong ER effects [10]. In this paper, compressive behaviors of ER fluids based on zeolite and silicone oils under different initial gap distances, different applied voltages, and at a small compressive speed were investigated. Deviations from the traditional description have been found and discussed.

II. EXPERIMENT

The apparatus employed in this study is similar to that employed in our former report [9] as shown in Fig. 1. The upper plate connected to a force sensor has a rectangular shape $S=32\times 32\ \mathrm{mm}^2$. The lower plate is a little larger than the upper one. The stress-strain-type force sensor has a measurement range ± 198 N and a stiffness $K=503$ N/mm. The sensor signal is modulated by a strain amplifier (DH-5935) and then sampled by a computer. The ER fluid employed in the experiment is based on zeolite and silicone oil with a particle volume fraction of about 26%.

The test process is as follows. At first the distance between the two plates is adjusted to the initial gap distance. After a voltage V has been applied to the ER fluid, compression is carried out. The original gap distance between the two parallel plates h_0 has been set to 4, 2, 1, and 0.5 mm, respectively. The nominal final gap distance is 25% of the initial value. During the compressions, the applied voltage V is kept constant and is withdrawn after the compression. After the reset of the initial gap distance and the applied voltage, other compressions are carried out. Corresponding to different h_0, different V has been applied to keep the initial electric fields between the plates E_0 to be 0.25, 0.5, 0.75, 1, and 1.25 kV/mm, respectively. For instance, when $h_0=4$ mm, the applied voltages are 1, 2, 3, 4, and 5 kV, respectively. Also, the compressive speed is kept constant i.e., $v=0.4167$ mm/s. All the experiments have been done at room temperature 27 °C.

If the tested compressive force is F, the compressive stress P during the compressive process can be represented as

$$P=F/S. \tag{2}$$

The compressive strain γ is expressed as

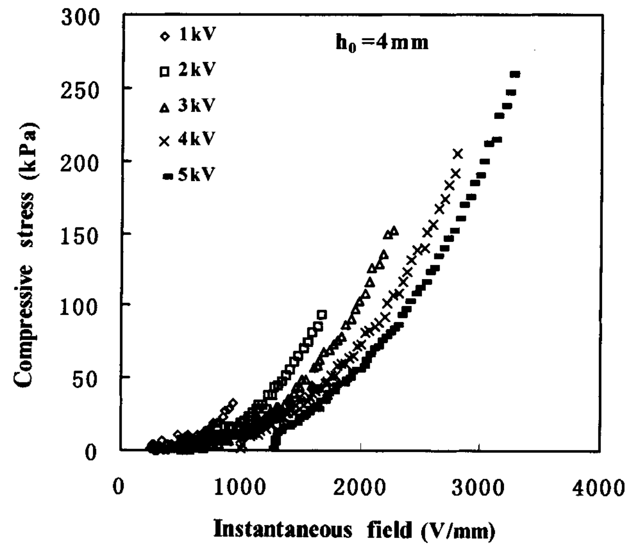

FIG. 2. Compressive stress P of compressions at an initial gap distance of 4 mm.

$$\gamma=\frac{1}{h_0}\left(vt-\frac{F}{K}\right), \tag{3}$$

where t is the compressive time. The instantaneous distance between the two plates h can be calculated from the compressive time t, the computer controlled compressing speed v, and the deformation of the force sensor as

$$h=h_0-vt+F/K. \tag{4}$$

The instantaneous electric field E during the compression process is calculated by

$$E=\frac{V}{h}. \tag{5}$$

Also, as mentioned above, when ER fluids are compressed at a small compressive speed, the contribution of the viscous force to the compression stress can be neglected. In this investigation, the nominal compressive speed is as low as 0.4167 mm/s, the viscosity of the ER fluid under no field is about 8 Pa s at room temperature 25 °C. Neglecting the viscous force at the small compressive speed, the compressive stress during compression can be looked as all contributed by the field induced yield stress of the ER fluid, so the nominal yield stress of the ER fluid during compressions can be approximated by the following equation:

$$\tau_0=\frac{3Ph}{D}. \tag{6}$$

III. RESULTS AND DISCUSSIONS

The compressive stress versus the instantaneous electric field of compressions when $h_0=4$ mm is shown in Fig. 2. The compressive stress increases quickly with the increase in the instantaneous electric field. Because the applied voltage is constant during compressions, the decrease in h causes the

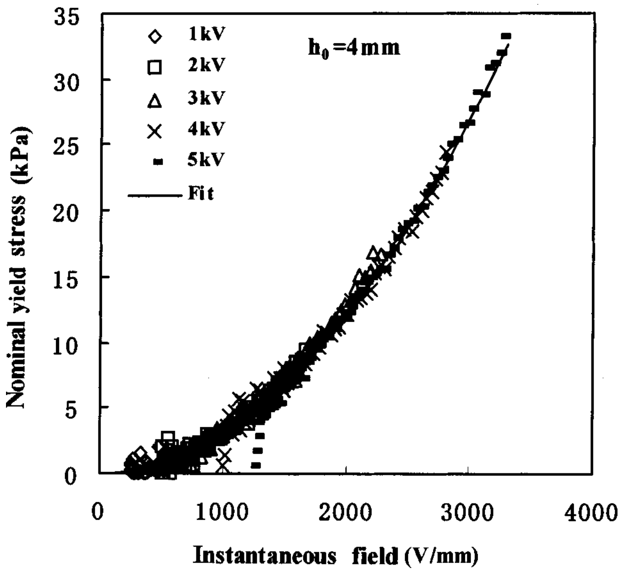

FIG. 3. Nominal yield stress τ_0 of compressions at an initial gap distance of 4 mm.

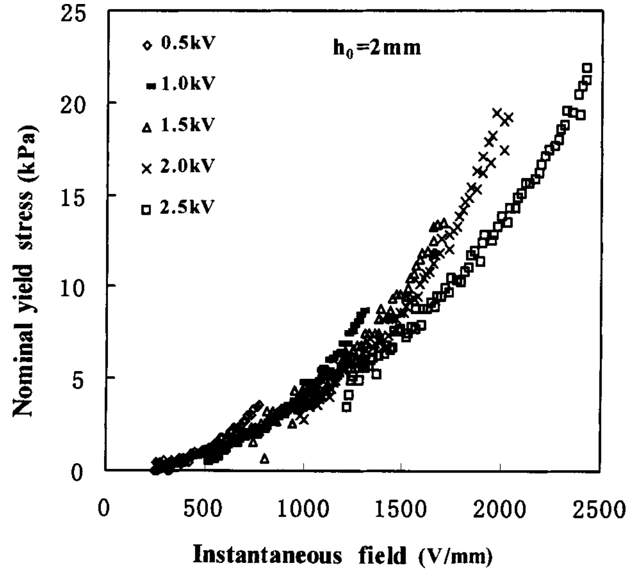

FIG. 4. Nominal yield stress τ_0 of compressions at an initial gap distance of 2 mm.

increase in electric field E. Also, under a certain instantaneous electric field, compressive, stress of compression applied at a higher applied voltage is obviously lower than that applied at a lower applied voltage but experienced a larger compressive strain. This can be explained by the fact that the compression experienced by a larger compressive strain has a smaller h and a higher D/h. The ER fluid have the same τ_0 under the same instantaneous field; then according to Eq. (6), the later compressive stress will be higher than the former one. The nominal yield stress calculated according to Eq. (6) when $h_0 = 4$ mm is shown in Fig. 3. The curves applied different voltages overlap over most of the ranges, showing that the five compressions can be well described by the principle represented by Eq. (6). The overlapped curves can be fitted by the following equation, whose curve is also shown in Fig. 3:

$$\tau_0 = 3\times 10^{-6} E^2. \tag{7}$$

The equation shows that the nominal yield stress is proportional to the square of the external electric field. This square relationship is usually reported for static yield stress of ER fluids to the applied electric field [17]. Many experimental reports about shear yield stress of ER fluids show an exponent of about 1.4–1.6 [18]. Therefore we call the stress obtained from Eq. (6) nominal yield stress rather than shear yield stress. However, whatever it is called, Fig. 3 shows that the compressions at this gap distance can be well described by the traditional principles of the continuous media theory that can be simplified to Eq. (6) at small compressive speeds. Also, Figs. 2 and 3 show that there is a very small nominal yield stress during compression until the field has increased substantially and it seemed to disagree with the fact that the higher the field the stronger the ER fluid. This can be ascribed to the elasticity of ER fluids before they yield. ER fluids usually experience a little strain to reach their yield stress that can be described by the biviscosity model [14–15,19]. The compressive strain change corresponds to the field increase in our experiment. This part has not reached the yield stress and is not discussed in this investigation. The phenomenon is also observed in other compressions of ER fluids [6,9].

When $h_0 = 2$ mm, the nominal yield stress is shown in Fig. 4. The nominal yield stresses under different applied voltages are no longer well overlapped as that shown in Fig. 3. Fitting the curves in Fig. 4 with exponential functions, the equations for the curves are $\tau_0 = 2\times 10^{-2} E^{2.83}$ (0.5 kV), $\tau_0 = 2\times 10^{-7} E^{2.42}$ (1 kV), $\tau_0 = 6\times 10^{-7} E^{2.27}$ (1.5 kV), $\tau_0 = 2\times 10^{-7} E^{2.45}$ (2 kV), and $\tau_0 = 1\times 10^{-6} E^{2.18}$ (2.5 kV). The nominal yield stress is no longer proportional to the square of the external electric field.

With the further decrease in h_0 to 1 mm, the difference between curves becomes more significant, as is shown in Fig. 5. Curves are obviously different from each other and have no overlap parts. Figure 5 also shows a trend that the exponent increases with increase in the applied voltage. The exponential function for the curve of 1 kV is $\tau_0 = 1\times 10^{-6} E^{5.52}$. τ_0 depends much strongly on the electric field than that of 0.25 kV given by $\tau_0 = 1\times 10^{-7} E^{2.73}$. Figure 6 shows the results when $h_0 = 0.5$ mm. A nearly straight increase in nominal yield stress with increase in electric field is shown. When the applied voltage increased from 0.125 kV to 0.375 kV, the increase in nominal yield stress versus electric field accelerated. When an applied voltage 0.5 kV is used, the electric field changed very little during the compression. Due to the accuracy of the elasticity of the force sensor, the compressive feeding speed and the compressive displacement, the instantaneous field even decreases a little in the beginning when the ER fluid is compressed for 0.375 and 0.5 kV. In fact, the compressive displacement is approximately totally compensated by the deformation of the force sensor, remaining a constant instantaneous field. Due to the above system error, a very small negative compressive strain has

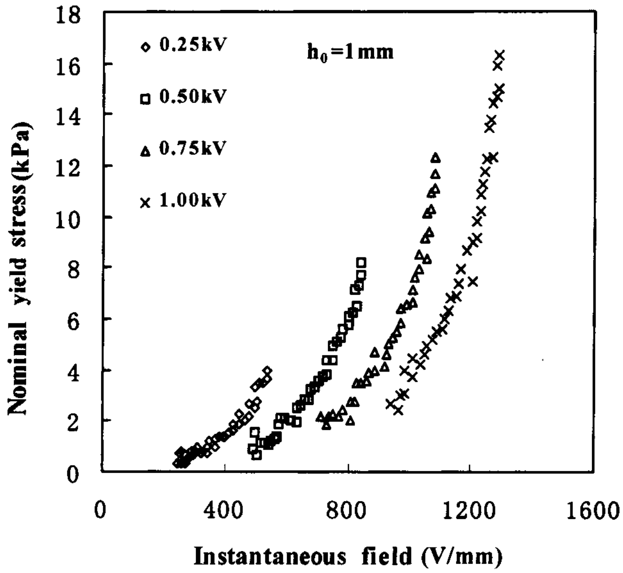

FIG. 5. Nominal yield stress τ_0 of compressions at an initial gap distance of 1 mm.

been calculated and thus shows a small decrease in the instantaneous field. But, as it should be recognized, this part is a straight increase in the normal yield stress at approximately constant instantaneous fields in the beginning, showing a very strong stiffness of the ER fluid under the conditions.

For each initial gap distance, E_0 has been, respectively, set to 0.25, 0.5, 0.75, 1, and 1.25 kV/mm. Except for 1.25 kV/mm when $h_0 = 1$ mm and $h_0 = 0.5$ mm, the ER fluid showed too strong stiffness. Comparing the tested nominal yield stresses of compressions at different initial gap distances h_0, the nominal yield stresses when $E_0 = 0.5$ and 0.75 kV/mm are shown in Figs. 7 and 8, respectively. The nominal yield stress at a smaller h_0 is obviously higher than that at a larger h_0 under the same instantaneous field.

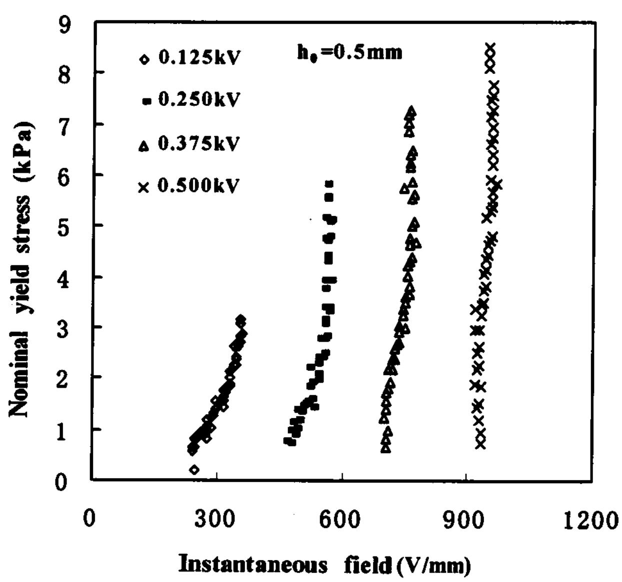

FIG. 6. Nominal yield stress τ_0 of compressions at an initial gap distance of 0.5 mm.

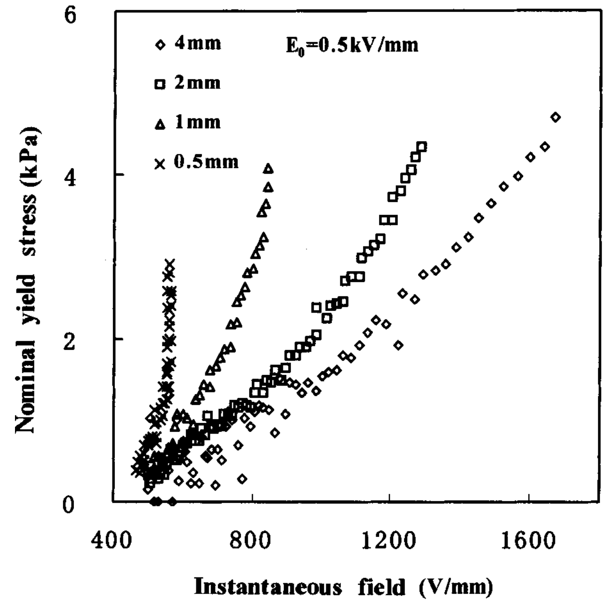

FIG. 7. Nominal yield stress τ_0 of ER fluids at an initial electric field of 0.50 kV/mm and different initial gap distances.

In this investigation, the nominal compressive speed is 0.4167 mm/s. The viscosity of the ER fluid under no field is about 8 Pa s at room temperature of 25 °C. During compressions, the force sensor has a low stiffness and a large deformation. At the end of compressions, the compressive speeds are, respectively, 0.183 mm/s ($h_0 = 4$ mm, 5 kV), 0.069 mm/s ($h_0 = 2$ mm, 2.5 kV), 0.038 mm/s ($h_0 = 1$ mm, 1 kV) and ≈0.007 mm/s ($h_0 = 0.5$ mm, 0.5 kV). According to the theoretical calculation [14,15,19], the contribution of the viscous force to the compressive stress is less than 0.5%. The viscous force contributes very little to the tested nominal yield stress and can be neglected. The tested nominal yield

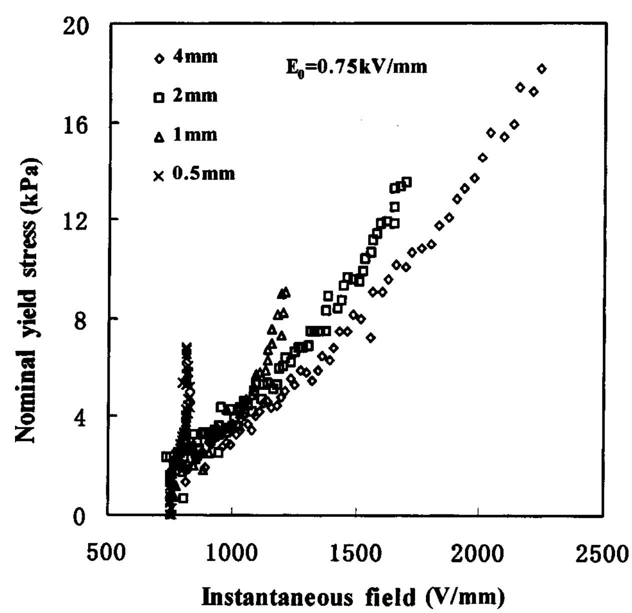

FIG. 8. Nominal yield stress τ_0 of ER fluids at an initial electric field of 0.75 kV/mm and different initial gap distances.

stress can be considered totally contributed by the field induced resistance of the ER fluid. The deviation of the nominal yield stresses from the description by Eq. (6) is dealt with the field induced yield stresses. As mentioned above, similar deviations have also been reported by Noresson and Ohlson [8]. They found that the Bingham parameters tested from shear-flow mode are not valid for the calculation of the squeeze-flow mode behavior employing the continuous media theory. Different from our simplified calculation, their method is an accurate numerical calculation based on the traditional principles of fluids. They also found that the Bingham parameters directly obtained from the squeeze-flow mode are valid for one amplitude and one frequency only. If we still want to describe the squeeze-flow of ER fluids by employing the Bingham parameters and the traditional continuous media theory, such as experiments done by us and by Noresson and Ohlson, the Bingham parameters should have a different set of values at different conditions. This is not in accord with the fact that there is only one set of Bingham parameters for a given ER fluid. These experiments show that the description of compressive behavior of ER fluids with the continuous media theory and the Bingham model might not have reflected the essential property of the ER effect during compression.

Considering the basic phenomena in the ER effect, ER suspensions are composed of fine particles and insulating oils; when an external electric field is applied on the suspensions, the particles are polarized and strongly interact with each other to form regular chains and columns along the field direction. Similar to the sheared ER fluids involving the interaction forces between particles along the shear direction and the deformation of particle chains along the shear direction perpendicular to the applied field, the mechanical property of ER fluids under compression is also determined by the chain strength and the deformation of the chains under compression. For an ER fluid compressed at a small compressive speed, the compression stress is mainly contributed by the resistances of the chains induced by the external electric field. As the employed particles in ER fluids are usually of the size of micron scale, and the gap distance is of millimeter scale, so the particle chains can be seen as slim rods. According to the mechanics of compressing slim rods, the rod strength P_L is determined by the rod length l and rod diameter d by the following equation [20]:

$$P_L = k_G \left(\frac{d}{l} \right)^2, \tag{8}$$

where k_G is a material parameter, which, for ER fluids, should be tightly related to the particle interactions. Therefore, for ER fluids under compression, if the diameter of the chains is constant, the chain strength will be greatly improved by increasing k_G through increasing the applied electric field and the decrease in the chain length $l = h$. At some places, for instance, when the applied initial field strength is 0.25 kV/mm, the square relationship between the compressive stress and the chain length or the gap distance is satisfied. But as shown in Figs. 7 and 8, the square relationship is not always satisfied. This can be ascribed to the fact that the assumption of single chain is not always applicable; for ER fluids under high electric fields, columns composed of several chains are usually observed. This has an effect of increasing the rod diameter d. Also, compression may decrease the distance between particles that can greatly increase the interaction force between particles and may shape more compact structures that bring a higher yield stress of ER chains, and thus increase the material property factor k_G. This structure strengthening effect is similar to that reported by Tang *et al.* [21]. The yield stress of ER fluids and magnetorheological (MR) fluids can be significantly strengthened by applying a pressure. They also showed that images of the particle chains get shorter and are pushed close to form a close-packed structure. This close-packed structure has the similar effect of increasing column diameter. The structure transformation during the compression of ER fluids should be similar to that of MR fluids. The description of the compression of ER fluids directly from the chain strength under compression is reasonable and attractive. But to derive the compression stress from the chain strength, much work still needs to be done.

IV. CONCLUSION

In this investigation, compressions of ER fluids based on zeolite and silicone oils have been carried out under different initial gap distances and different applied voltages at a slow compressive speed. At an initial gap distance of 4 mm, the compressive curves of nominal yield stress overlapped well, and can be well described by the traditional continuous media theory. With the decrease in gap distance, the nominal yield stresses are no longer overlapped. The difference between the nominal yield stress curves increased with a decrease in the gap distance and an increase in the applied voltages. Also compared with the reports of other researchers, it shows the failure of the traditional description of the compression of ER fluids based on the Bingham model and the continuous media theory. Directly analyzing the compression of particle chains in ER fluids, whose strength is affected by the field strength, the diameter and the length of the particles chains are considered nearer to the essential property of ER fluids under compression than that described by the traditional models.

ACKNOWLEDGMENT

This work was sponsored by the National Natural Science Foundation of China (Grant No. 50202010).

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