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# Squeeze behavior of magnetorheological fluids under constant volume and uniform magnetic field

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## Abstract

In this work the experimental investigation of magnetorheological fluids in squeeze mode has been carried out under constant volume with a self-developed device. The magnetorheological fluids were forced to move in all directions in a horizontal plane as the two flat surfaces came together. A pair of Helmholtz coils was used to generate a uniform magnetic field in the compression gap. The normal forces within the gap were systematically studied for different magnetic field, squeeze velocity, particle concentration, viscosity of carrier fluid and initial gap distance. Two regions of behavior were obtained from the normal force versus gap distance curve: elastic deformation and plastic flow. A power law fitting was appropriate for the relation between the normal force and the gap in the plastic flow. The index of the power law was smaller than that predicted by the continuum theory, possibly due to the squeeze strengthening effect and the sealing effect.

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Magnetorheological (MR) fluids are a class of smart materials whose rheological properties can be controlled by an external magnetic field. MR fluids are composed of magnetizable particles, carrier fluid and additives, which behave like Newtonian fluids in the absence of a magnetic field. After a magnetic field is applied, the particles suspended in the carrier fluids arrange themselves to form chains, columns and even intricate networks. Because of their fast, reversible and repeatable change, MR fluids provide an efficient way to design simple and fast electromechanical systems for damper, actuation, valve and motion control [1–4]. According to the flow mode, all devices that use MR fluids can be classified as the shear mode, valve mode, squeeze mode or their combination. Among the three modes, it is well known that the squeeze flow mode provides the largest yield stress under the same field. The properties of MR fluids in the shear or valve mode have been

extensively investigated, but an understanding of the behavior of a MR fluid in the squeeze mode is still far from complete [5–7].

The squeeze flow of MR fluids is flow in which MR fluids are compressed between two parallel plates and then squeezed out radially. This mode is often used for some small amplitude vibration dampers. For small motions, it offers the possibility of very large forces which can be controlled by the MR effect. First reports on squeeze behavior of MR fluids were the so-called squeeze strengthening effect [8, 9]. The yield shear stress was enhanced by the formation of thick strong columns under compression and friction effects between the particles. In accordance with the loading method, the investigation of the compression behaviors for the MR fluids could be divided into two categories. The first one was the oscillatory compression mode, in which the gap distance between the plates changed in a sinusoidal way and the oscillatory amplitude was only a few per cent of the initial gap distance [5, 10–12]. The

hysteretic loops of the MR fluids under the oscillatory squeeze mode indicated that the damping force and the area of the hysteretic loop of MR fluids increased with the amplitude of the current and strain. Moreover, the peak compressive force increased with increasing cycle number, which was called clumping behavior. The second investigation method for the compression mode is unidirectional monotonous compression. A reduction in the gap could be achieved to a large extent, but the squeezing velocity was often limited to a small constant value [7, 13, 14]. The results showed that the compressive stress was much larger than the tensile and shear stress. Three regions were found through the stress–strain curves, related to the relative movement between the particles and the carrier liquid in the MR fluid.

On the basis of the geometry between MR fluids and plates in the squeeze mode, there were two methods selected: constant area and constant volume. In the constant area geometry, the sample radius was equal to or larger than that of the plates, and the sample flowed out during compression. Most of the squeeze flow studies on MR fluids have used constant area compression [5, 7–14]. One drawback of this method was that the concentration of particles between the plates changed due to the fluid being squeezed out during compression (sealing effect). This restriction can be avoided by using constant volume apparatus [6, 15]. In the constant volume geometry, the plates were larger than the sample and the radial interface was free. De Vicente *et al* [6, 16] investigated unidirectional monotonic compression tests of MR fluids under constant volume operation. They proposed a unified description for the MR fluids in terms of a continuous media theory for plastic materials. This allowed them to collapse compression curves obtained for a wide range of magnetic field strengths, medium viscosity and particle concentration. In principle, when a MR fluid was compressed under a constant volume in a uniform magnetic field, the change of compressive stress indicates mostly the change of the structure parameter in the MR fluids.

For all the reported self-assembled devices [5, 7–14] and commercial setups [6, 16], the radial magnetic fields were not uniform, and a magnetic field gradient always existed under a given current. The nonuniform field would change the properties of field-responsive materials greatly, and the inhomogeneity of the applied field could cause the appearance of normal forces in MR fluids [17, 18]. Therefore, the compression properties of MR fluids are inevitably affected by this nonuniform field. Compression behaviors of MR fluids under completely uniform fields have not been studied. In this work, the compression properties of MR fluids under constant volume and uniform magnetic field were investigated by using a self-developed device. Influential factors, including the magnetic field, compression velocity, initial gap distance, volume concentration of iron particles, and viscosity of the carrier fluid were systematically investigated. This provided research results of the basic behavior and performance of MR fluids in the squeeze mode.

## 2. Experimental details

### 2.1. Materials

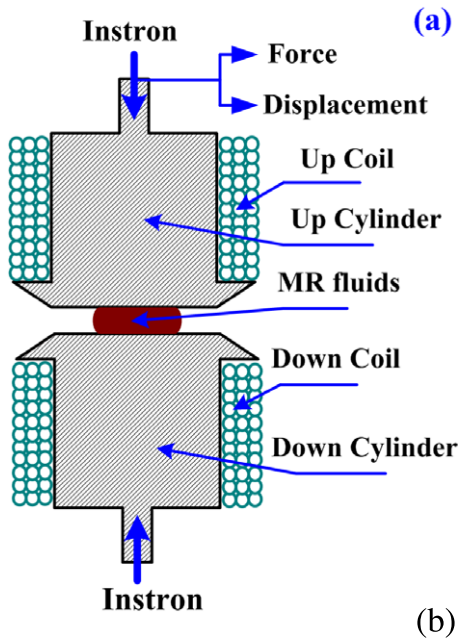
The MR fluids were composed of carbonyl iron powder particles in silicone oil. The carbonyl iron particles were purchased from BASF (model CN) and had an average particle size of about 6  $\mu\text{m}$ . Silicone oil (H201) was from Sinopharm Chemical Reagent Co. Ltd and three different viscosities (10, 100, 500 cSt) were prepared. A small amount of stearic acid (2 wt%) was added to improve stability. Five different MR fluids with iron particle volume fractions of 10%, 15%, 20%, 25% and 30% were prepared. The samples were vigorously shaken to ensure the required homogeneity before measurements.

### 2.2. Apparatus

A test rig was designed to perform the squeeze mode measurements. As shown in figure 1, the compression of the MR fluids was carried out between the two identical parallel plates with diameters of 50 mm. The two cylinders were made from magnetic materials and were tightly connected to the grips of INSTRON (model E3000). Samples were placed between the parallel plates. The top cylinder was lowered at a constant velocity to squeeze the MR fluids while the bottom cylinder was fixed. A pair of Helmholtz coils with 3200 turns was wound around the cylinders to generate a uniform magnetic field. The displacement and force signals were sampled by a computer.

The magnitude of the magnetic field generated by the coils could be changed by adjusting the electric current density. A tesla meter from Shanghai Hengtong Company (model HT20) was used to measure the magnetic flux density between the plates. The magnetic flux density distribution without the MR fluid is shown in figure 2, where the gap size is set as 2 mm. A uniform field distribution could be found between the parallel plates, except at the rim of the plates, when a certain current is applied. The MR fluid is placed in the center of the plates during testing, so that an absolutely uniform field is obtained for the constant volume squeeze mode. With increasing electrical current, the magnetic flux density is increased (figure 3). The magnetic flux density with MR fluids (30% MR fluid) in the gap is almost the same as that without the samples, showing that a small amount of sample does not change the magnetic field. It should be noted that the magnetic flux density increases with decreasing gap size (figure 4), and an inverse relation could be obtained between them. This can increase the yield stress of the MR fluids and change their compression behavior.

After the electric current was applied, the two cylinders attract each other, leading to a spurious force for the squeezing of the MR fluids. This force should be subtracted. Therefore, squeeze measurements were carried out as follows. (1) 0.3 ml samples were placed between the parallel plates using a syringe. (2) The external magnetic field was suddenly applied for 60 s while the sample was kept stationary—this being long enough to allow the aggregates to form. (3) The compression

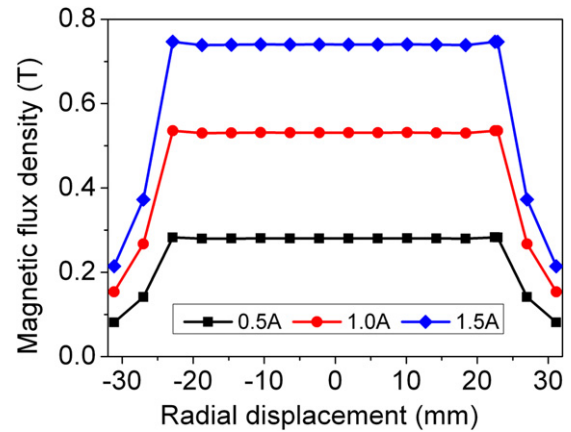


**Figure 1.** Schematic diagram (a) and picture (b) of the experimental setup.

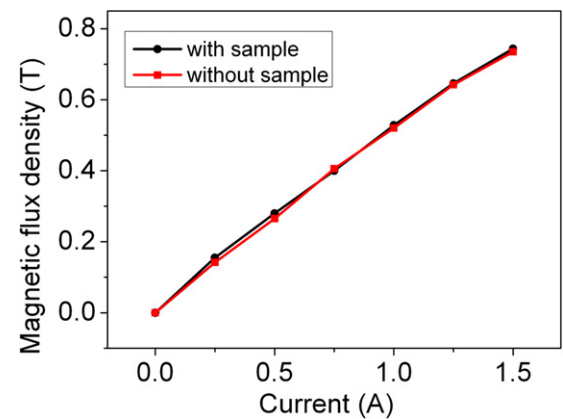
test was started at a constant approach speed in the presence of the magnetic field and the output signals of displacement and force were acquired. (4) The compression process was repeated without MR fluid while the displacement and force signals were sampled. (5) The results were obtained from the signals of step (3) minus those of step (4). In the tests the temperature was set at 25 °C.

### 3. Theoretical analysis

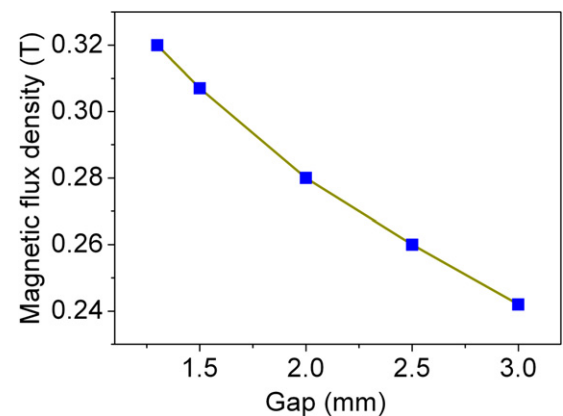
In the so-called filtration-dominated regime, de Vicente *et al* [6, 16] have proven the validity of continuous media theory for a Bingham plastic material in MR fluids under slow



**Figure 2.** Change of magnetic flux density with radial displacement for different currents without MR fluid between the plates.



**Figure 3.** Magnetic flux density for different currents, with and without samples.



**Figure 4.** Change in magnetic flux density for different gap sizes with a current of 0.5 A.

compression. After some algebra, the normal force  $F$  in the case of constant volume tests can be written as follows:

$$F = \frac{2\tau_y V^{3/2}}{3\pi^{1/2} h^{5/2}} \quad (1)$$

where  $V$  is the total volume of the MR fluid ( $V = \pi R^2 h$ ,  $R$  is the radius of the MR fluid),  $\tau_y$  is the shear yield stress of

the MR fluid and  $h$  is the gap distance. It can be seen that a power law ( $F \propto h^{-2.5}$ ) can be used to fit the normal force with the gap distance and the index of the power law relation is recognized as  $-2.5$ .

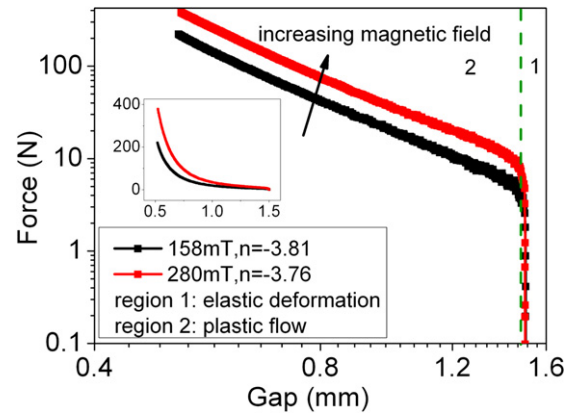
During compression, as shown in figure 4, the magnetic flux density is inversely proportional to the gap distance, namely  $B = c/h$  ( $c$  is constant). As is well known, the shear yield stress of MR fluid is a function of magnetic field. That is, the shear yield stress of MR fluids can be calculated by  $\tau_y = k_1 B^m$  ( $k_1$  and  $m$  are constant), where  $m = 2$  for small magnetic fields and  $m = 1.5$  for moderate fields. The shear yield stress eventually becomes independent of field strength at large field strengths [3]. Therefore, the shear yield stress has a relationship to the gap distance as  $\tau_y = k_2 h^{-m}$  ( $k_2$  is constant) in the squeeze mode. This shows that the shear yield stress will be increased with decreasing gap distance. Substituting this relation into the expression (1), the normal force during compression can be obtained from  $F = kh^n$  ( $k$  and  $n = -m - 2.5 > -4.5$  are constant, and  $k$  is related to the material and device parameter). In addition, the squeeze strengthening effect and the sealing effect also affect the normal force of the squeeze mode, changing the power law index of the normal force with the gap distance greatly [16, 18].

## 4. Results and discussion

### 4.1. Effect of magnetic field on the normal force

Compression tests without a magnetic field were first carried out, showing that the normal force was less than 0.1 N and thus is discarded for brevity. The static normal force under a magnetic field was also neglected. Next, experiments were conducted under a constant current to test the magnetic-dependent normal force. Figure 5 represents the normal force versus gap distance under different magnetic fields. With decreasing gap distance the normal force clearly increases. Two regions could be obtained from the change of the normal force. In region 1 the normal force increases sharply from 0 to 8.37 N as the gap distance decreases from 1.5 to 1.47 mm for a 280 mT magnetic field. In region 2, the normal force increases from 8.37 to 393 N as the gap distance is reduced from 1.47 to 0.52 mm. A power law relation in the linear–linear plot or a linear relation in the log–log plot could be obtained for the normal force versus gap distance.

Region 1 can be called the elastic deformation region while region 2 is the plastic flow region. After applying the magnetic field, the iron particles in the MR fluid form chains or columns, and the MR fluid shows a transition from a liquid to a nearly solid state. As the squeeze operation proceeds, the gap distance is reduced. In the elastic region the particle chains or columns in the MR fluid remain intact without breaking. It resists the loading force via elastic deformation of the particles. In the plastic flow region the particle chains structure collapses at a critical stress level, then immediately forms a metastable structure again. The decreasing distance between the plates will induce particle chains to reorganize and form stronger and thicker column structures, which



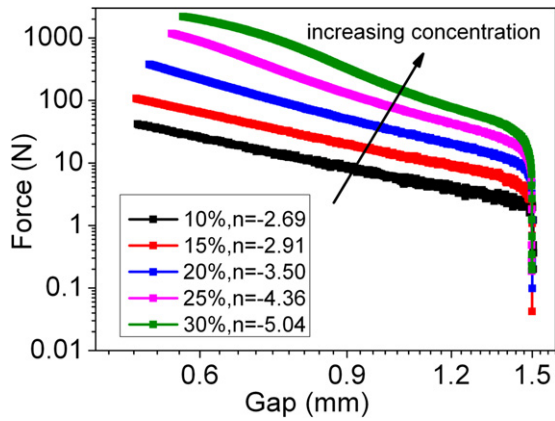
**Figure 5.** Change of the normal force with gap distance under different magnetic fields in a log–log plot (the inset is a linear–linear plot). The particle volume fraction of MR fluid is 20%, the viscosity of silicone oil is 500 cSt, the initial gap distance is 1.5 mm and the compression velocity is  $1 \text{ mm min}^{-1}$ .

will bring greater resistance. This process repeats as the compression proceeds and a fluctuating normal force can be found, similar to previous results [19]. The compressive yield stress (the transformation normal stress from the elastic region to the plastic region, where normal stress is defined as  $\tau_N = F/A$ , and  $A$  is the area of the plate) is about 41.9 kPa, which is much larger than the shear yield stress of 4.9 kPa. (The shear yield stress is found from shear stress–shear rate plots and is not shown here for brevity.) Much work has been done to demonstrate this [6, 7, 13, 14].

With increasing magnetic field the normal force increases for the same gap distance, which is a typical MR effect. The large magnetic field can increase the attracting force between the particles and form a stronger structure in the MR fluid, which needs a larger compressive force to break it. The compressive yield stress will be enhanced from 18 to 41.9 kPa as the magnetic field increases from 0.158 to 0.28 T. The same results have been obtained in previous research [6, 7, 13, 14, 16]. In addition, power law relation fitting is conducted and the indices are  $-3.81$  and  $-3.76$  for 0.158 and 0.28 T, in agreement with the theoretical analysis. Similar phenomena can be found for other samples and compression conditions.

### 4.2. Effect of particle concentration on the normal force

The squeeze behaviors for MR fluids with different particle concentrations are compared in figure 6. It can be found that at the same gap distance the normal force increases as the particle concentration increases. The compressive yield stress increases from 8 to 50 kPa as the volume fraction increases from 10% to 30%. As the volume concentration of the iron particles increases, more particles can be used to form chain or column structures, which can lead to higher normal forces. Moreover, the interparticle distance decreases in the constant volume sample with increasing particle concentration. This can enhance the particle interactions and achieve larger attractive forces, which give rise to a larger normal force. Similar results have been obtained by de Vicente *et al* [6, 16].

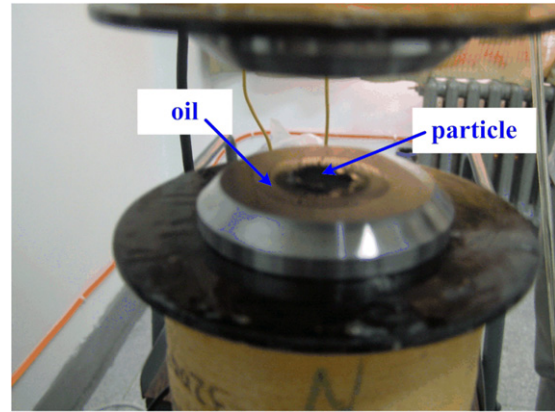


**Figure 6.** Change in the normal force with gap distance for different particle concentrations. The external magnetic field is 280 mT, the viscosity of silicone oil is 500 cSt, the initial gap distance is 1.5 mm and the compression velocity is 1 mm min<sup>-1</sup>.

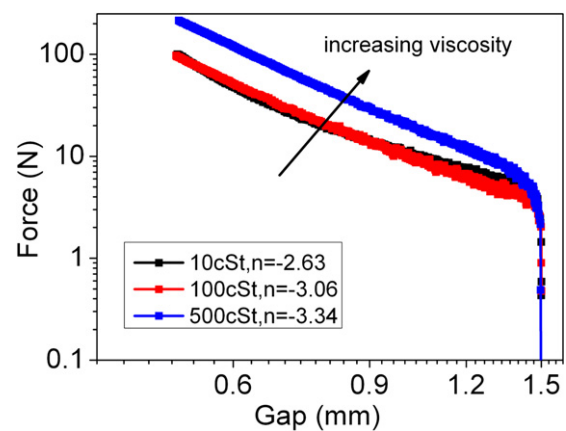
The power law indices of the low-concentration MR fluids (10%–25%) agree with the theoretical analysis (between  $-4.5$  and  $-2.5$ ). However, for the high-concentration MR fluid (30%) the index is less than  $-4.5$ , deviating from the theoretical analysis. The deviation suggests that the compression resistance generally increases faster than the prediction of the squeeze flow theory. On the one hand, the squeeze strengthening effect could cause this deviation [16, 18, 20]. The shear yield stress will be increased during compression, which enhances the normal force with decreasing gap distance. On the other hand, the MR fluid sample is carefully observed after the test, and the separation between the particles and silicone oil is found (figure 7). The particles gather together in the center of the plate while the silicone oil is at the rim. This sealing effect is often found in the constant area mode [21, 22], but it inevitably occurs for the high-concentration sample in the constant volume operation. During compression, the magnetic field will cause the particles to gather together and increase the local concentration of the MR fluid in the plate. The high-concentration MR fluid becomes even more concentrated with decreasing gap distance, thus enhancing the normal force greatly.

#### 4.3. Effect of carrier fluid on the normal force

Figure 8 shows data for several different viscosity silicone oils (10, 100 and 500 cSt) in MR fluid squeeze flow. It is found that the normal forces for 10 and 100 cSt silicone oil approximately overlap. However, as the viscosity of the oil increases to 500 cSt, the normal force clearly increases at the same gap size. Also, as the viscosity of the oil increases, the steepness of the curve (the index of the power law relation) decreases, as seen in a log–log plot. At a slow squeezing speed the viscous forces are minimized and the viscosity of the carrier fluid still has a strong effect on the behavior of the fluid. The high-viscosity oil contributes to the force more than the low-viscosity oil, and the force increases more quickly. It can be presumed that the high-viscosity carrier fluid can sustain the particle structure more effectively during compression.



**Figure 7.** The separation between the particles and silicone oil in the 30% MR fluid.

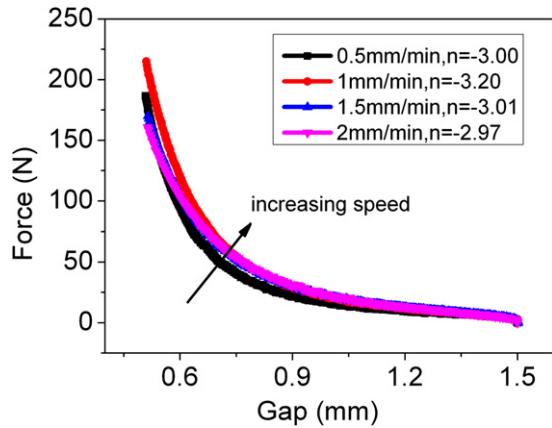


**Figure 8.** Change in the normal force with gap distance for different silicone oils. The external magnetic field is 280 mT, the particle concentration of the MR fluid is 15%, the initial gap distance is 1.5 mm and the compression velocity is 1 mm min<sup>-1</sup>.

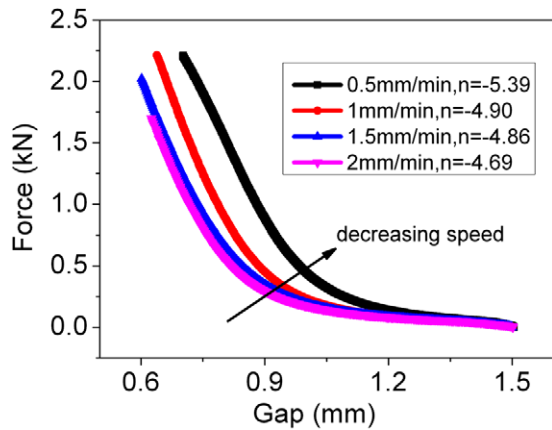
#### 4.4. Effect of squeeze velocity on the normal force

The effect of squeeze velocity on the normal force of the MR fluid is studied. Four small velocities from 0.5 to 2 mm min<sup>-1</sup> are tested (compressive rate range: 0.0056–0.022 s<sup>-1</sup>); they are also believed to be quasi-static compression. For the 15% MR fluid (figure 9), the squeeze velocity has a very small effect on the force–gap relationship and can be neglected. The same characteristics are observed at all values of the compressive speed. This result is similar to a previous investigation [14]. The index of the power law relation is around  $-3.0$ , which agrees with the theoretical analysis. In this case the squeeze velocity has little effect on the particle structure during compression.

However, for the 30% MR fluid (figure 10), with decreasing squeeze velocity the normal force is increased. Under these conditions, slower speeds actually produce larger forces at similar gaps. This is the opposite of what is expected in squeeze flow. Notice that decreasing the speed not only increases the force at the same gaps, as shown in figure 10, but even the slopes in the log–log plot become greater as the speed decreases. This result is similar to that for ER fluids [21,



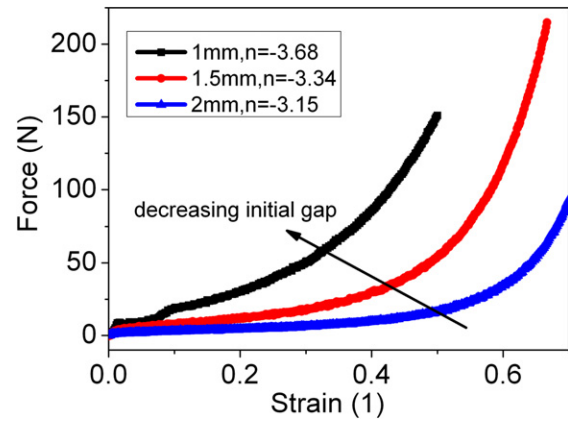
**Figure 9.** Change in the normal force with gap distance for different squeeze velocities. The external magnetic field is 280 mT, the particle concentration of the MR fluid is 15%, the viscosity of oil is 500 cSt and the initial gap distance is 1.5 mm.



**Figure 10.** Change in the normal force with gap distance for different squeeze velocities. The external magnetic field is 280 mT, the particle concentration of the MR fluid is 30%, the viscosity of oil is 500 cSt and the initial gap distance is 1.5 mm.

23]. The index of the power law relation between the normal force and the gap size is less than the theoretical analysis, which also arises from the squeeze strengthening effect and the sealing effect.

The different results for the effect of squeeze velocity on the normal force mainly come from the concentration of MR fluid, which can be explained by the effect of speed on the structuring of the MR fluids [21]. During compression, there must be a speed where the deformation of the particle structures proceeds at a rate too fast for stronger particle structures to be able to be reform. This speed, termed the upper limit squeezing speed for MR fluids, depends on the strength of the particle structures. For the low-concentration MR fluid, the squeeze velocity is above the upper limit squeezing speed, and there would be little difference due to changes in speed in the mechanical behavior of the MR fluids under a magnetic field. However, for the high-concentration MR fluid, the squeeze velocity is below this upper limit squeezing speed, and the reconstruction of particle structures would occur at an increasing rate as the compression speed



**Figure 11.** Change in the normal force with compressive strain for different initial gap sizes. The external magnetic field is 280 mT, the particle concentration of the MR fluid is 15%, the viscosity of oil is 500 cSt and the compression velocity is 1 mm min<sup>-1</sup>.

decreased. This is seen to be the case in figure 10 for the high-concentration sample, where stronger structures are formed at slower speeds.

#### 4.5. Effect of initial gap size on the normal force

Different initial gap distances ( $h_0 = 0.5, 1, 1.5$  mm) were tested to study their effect on the MR fluid compression behavior (figure 11). The normal force with the compressive strain (defined as  $\varepsilon = (h_0 - h(t))/h_0$ , where  $h(t)$  is the transient height during compression) is shown here in order to compare the normal force more directly. Clearly, a smaller initial gap distance can generate larger normal force at the same strain. This result is contrary to the results of Mazlan *et al* [13], which showed that higher values of compressive stress were required when the initial gap size was set to 2 mm than when the initial gap size was set to of 1 mm. However, it agrees with the result for ER fluids by Tian *et al* [20]. It is believed that the particle chains in the MR fluid can be seen as slim rods. According to the mechanics of compressed slim rods, the rod strength is determined by the rod length  $L$  with a relation to the length as  $F \propto L^{-2}$ . This means that shorter rods can support higher loadings and a smaller initial gap size produces a larger normal force. Also, the magnetic field at small gap size is larger than that at large gap size, which leads to larger normal forces at small gap sizes. So, when the initial gap distance increases, the chain's capacity to bear the loading force will weaken and the normal force decreases. Also, the power law index increases a little as the initial gap distance decreases.

## 5. Conclusion

In this work the squeeze behavior of MR fluids was investigated under constant volume operation. A test rig was designed and manufactured to carry out this experiment that could produce absolutely uniform magnetic fields. The compressive yield stress of MR fluids is much larger than the shear yield stress. The normal force increases with decreasing gap distance. Two regions could be obtained from the normal

force–gap distance curve: an elastic deformation region and a plastic flow region. A power law relation can capture the relation between the normal force and the gap distance in the plastic flow region. With increasing external magnetic field, particle concentration and viscosity of carrier fluid, the normal force increases, whereas with increasing initial gap distance the normal force decreases. For the low-concentration MR fluid the squeeze velocity has little effect on the normal force. However, the normal force increases with decreasing squeeze velocity for the high-concentration MR fluid. Moreover, a separation between the particles and carrier fluid during compression also occurs in the constant volume operation.

## Acknowledgments

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