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COMPARISON OF ELECTRORHEOLOGICAL BEHAVIOUR OF MINERAL AND TRANSFORMER OIL CONTAMINATED BY STARCH

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ABSTRACT : *Electrorheological fluids consist of finely divided polarizable particles suspended in non-conducting fluid. When an external electric filed is applied to such suspension, it exhibits large reversible changes in its rheological behaviour. These changes have been exploited in engineering practices for the development of discrete devices. While designing such devices, electrorheological properties of the fluid is required. In this work, the electrorheological properties of mineral oil and transformer oil contaminated by corn starch were explored using a concentric cylinder viscometer. Four different weight fractions of corn starch suspensions in mineral oil and transformer oil were tested at ambient temperatature of 25-30 ^{0}C. The relationship among the shear stress, shear strain, and fraction of the starch in the base fluids to the applied electric field were compared experimentally.*

KEYWORDS : *Electrorheological Fluids, Cylindrical Viscometer, Bingham Fluid, Electrical Field*

NİŞASTA KATKILI MİNERAL VE TRAFO YAĞLARININ ELEKTRORHEOLOJİKAL DAVRANIŞLARININ KARŞILAŞTIRILMASI

ÖZET : *Elektrorheolojik akışkanlar, iletken olmayan akışkanın içerisine çok küçük parçacıklara ayrılmış polarize olabilen taneciklerin katılmasıyla oluşturulurlar. Böyle bir karışıma dışarıdan elektrik alanı uygulandığında, akışkanın rheolojik davranışında büyük oranda tersinir değişiklikler gösterir. Bu değişimler mühendislik uygulamalarında alternatif aletlerin geliştirilmesini sağlamıştır. Böyle bir aletin tasarımı için öncelikle kullanılacak akışkanın elektrorheolojik özelliklerinin bilinmesi gerekmektedir. Bu çalışmada, mineral ve trafo yağları mısır nişastası ile karıştırılarak, bu yağların elektrorheolojikal özellikleri silindirik viskoz ölçer yardımıyla elde edilmiştir. Dört farklı ağırlık oranlarında yapılan mineral yağı-mısır nişastası ve trafo yağı-mısır nişastası karışımları ortam sıcaklığı olan 25-30 ^{0}C'de deneyleri yapılmıştır. Deneysel olarak mısır nişastası katkılı yağların, elektrik alanına karşılık kesme stresleri ve kesme gerilimleri arasındaki ilişki karşılaştırılmalı olarak elde edilerek sunulmuştur.*

ANAHTAR KELİMELER : *Elekrorheolojikal Akışkan, Silindirik Viskoz ölçer, Bingham Akışkan, Elektrik Alanı*

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I. INTRODUCTION

An electrorheological (ER) fluid is a mixture of finely divided particles suspended in a non-conducting base. If an external electric field applied on an ER fluid, the particles of the ER fluid is charged and arrange themselves like chains, between electrodes. In this way, flow resistance and applied stress on electrodes can be increased. This effect is proportional to the electric field applied, and it is reversible and fast acting.

This special characteristic of the ER fluids allow some potential applications. Flow, squeeze-flow and shear modes are three major application methods of the ER effect in practical devices. The fluid is pumped through a valve which consists of fixed electrodes in flow modes. The ER fluid is sandwiched between two electrodes in squeeze-flow mode. In shear mode, the electrodes of the ER fluid devices are free to rotate or translate in relation to each other. Control of the shear properties of the fluid leads to application torque transmission such as clutches (Stevens, at al and Monkman) [1-2], brakes (Duclos, at al) [3], shock absorbers and vibration dampers (Markis, at al) [4], etc . Increasing of the shear stress with the applied electric field is the important performance characteristics of the ER fluids and it was detected by using Rotational viscometer and Oscillatory viscometer. Klass and Martinek [5] have used Rotational viscometer to observe the increase in viscosity with electric field. But the stiffening and consequent ability of ER fluids to transmit forces is due to rheological characteristics and not due to a viscosity change. Since that time, numerous investigators have studied rheological behaviour by same method.

In this work, firstly, well known idealised behaviour of the ER fluids was briefly explained for completeness of the paper. Secondly, mineral oil and transformer oil based ER fluids were produced by mixing corn starch in different weight ratios. Then, the shear mode rheological behaviour of these fluids were tested as a function of electric field intensity by rotational viscometer which was designed for this purpose. Finally, experimental result indicating the relations among the different mixture ratios, shear stress, shear rate, and electric field intensity were given in graphical forms.

II. IDEALISED BEHAVIOUR OF ER FLUIDS

The relationship between shear stress and shear rate is the most important parameter in understanding this behaviour. ER fluids have been modelled as Bingham plastics which means that flow is observed only after exceeding a minimum yield stress. Idealised behaviour of the ER fluid is shown in Figure 1.

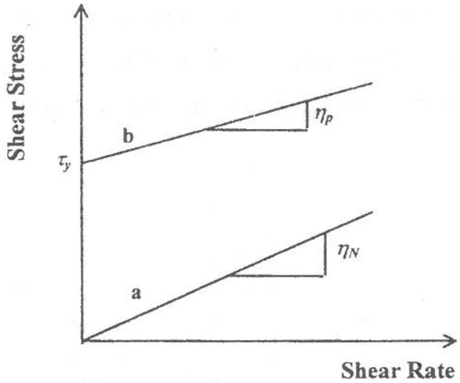


Figure 1. Ideal behaviour of ER fluid.

Line "a", in Figure 1, shows the characteristics of Newtonian fluids and line "b" shows the characteristics of Bingham plastics. Slopes of these lines are the dynamic viscosities of fluids. With no electric field applied an ER fluid behaves like a Newtonian fluid and the applied stress will cause the liquid to flow. Equation 1 is a first order model approximating the behaviour of a Newtonian fluid.

$$\tau = \mu_N \partial u / \partial y \quad (1)$$

Where μ_N is the Newtonian viscosity in Pa.s, $\partial u / \partial y$ is the shear rate in s^{-1} and the τ is the shear stress in Pa.

Flow only occurs for a stress greater than the yield stress in Bingham plastics. Below the yield stress, applied stress will strain the plastic but not cause it to flow. The equation for a Bingham body is:

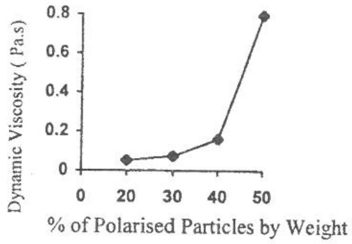
$$\tau = \tau_y + \mu_p \partial u / \partial y \quad (2)$$

Where τ is the shear stress in Pa, τ_y is the yield stress in Pa, μ_p is the plastic viscosity in Pa.s. The yield stress increases proportional to the applied electric field while the plastic viscosity unchanged [6].

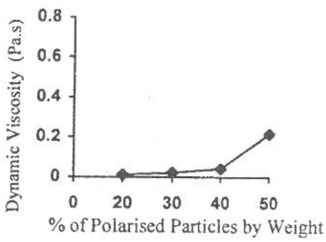
III. EXPERIMENTAL INVESTIGATION

III. 1 Electrorheological Fluids Used in Experiments

The ER fluids used in rotational viscometer tests comprised of mineral oil and transformer oil containing corn starch. Dynamic viscosity and density of mineral oil are 0.041 Pa.s and 900 kg/m^3, respectively. 0.0074 Pa.s is the dynamic viscosity and 840 kg/m^3 is the density of transformer oil. These fluids are mixed with corn starch in different weight ratios. Figure 2 (a) and (b) show the effect of mixing ratios on dynamic viscosity of mineral oil and transformer oil-based ER fluids, respectively.



(a)



(b)

Figure 2. Dynamic viscosity of mineral oil-based (a) and tranformer oil-based (b) ER fluids.

The comparison of dynamic viscosity both mineral oil-based and transformer oil-based ER fluids is rather good for no-field viscosity up to about 50% weight ratios. The dynamic viscosities increase drastically above this ratio, even ER fluids lose their fluid properties.

III. 2 Experimental Set-up

The rheological behaviour of the ER fluids can clearly be seen by plotting the change in shear stress with respect to shear rate under the influence of electric field. These flow curves, as depicted in Figures 4 to 11, are obtained by using rotational viscometer which comprises of two concentric cylinders with 0.8 mm radial separation of two faces as shown in Figure 3. An ER fluid is filled in this space. With no electric field present, rotating the inner cylinder creates the shear stress but little or no motion and torque on the outer cylinder. When the electric field is applied, the ER fluid stiffen with field strength and stress is transferred to the outer cylinder as a torque. When the electric field great enough, the ER fluid turns out to be like a solid and the cylinders behave as tough, they were pressed together with no fluid between them.

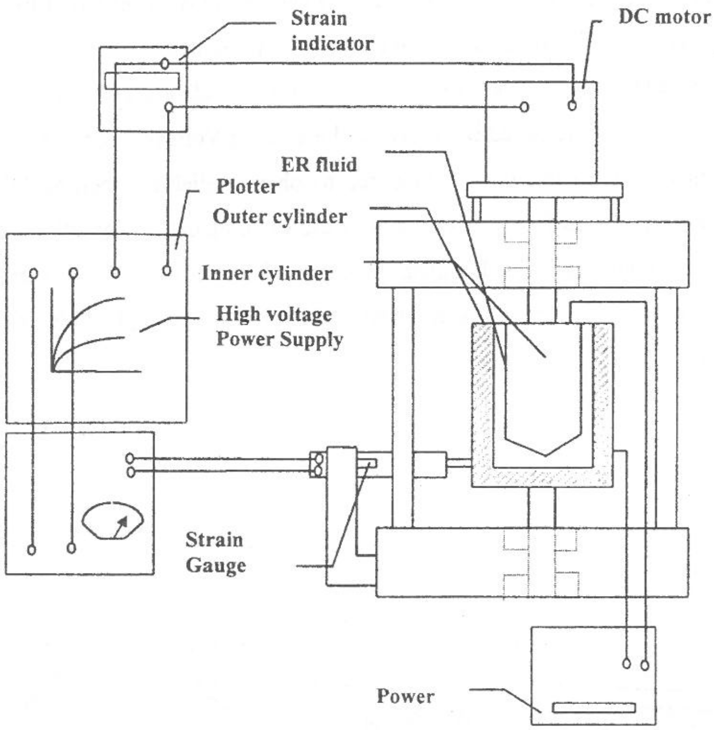


Figure 3. Rotational viscometer used in the experiments.

The electric field between two concentric cylinders is obtained from a high voltage power supply capable of providing voltages from 0-1000 Volts. Outer cylinder of the viscometer is connected to a cantilever beam on which two strain gauge were stuck. Transmitted stress is determined by using a strain indicator. The flow curves of the ER fluid were drawn by using a plotter. X direction on the plotter corresponds to the DC motor speed which is proportional to the shear rate and Y direction corresponds to the voltage of the strain indicator which is proportional to the transmitted stress. The speed of the inner cylinder is transformed to the shear rate and the voltage of the strain indicator is transformed to the shear stress. Thus, the output graph of the plotter is arranged with these new values.

III. 3 Experimental Results and Discussions

The variation of the transmitted torque or shear stress with electric field was investigated by using the rotational viscometer. Increase of the yield stress under the application of different electric fields on mineral oil and transformer oil-based ER fluids which contain corn starch in different weight ratios were presented.

Rotational viscometer results of the mineral oil-based ER fluids are given in Figures 4 to 7. The shear stress was measured by applying the electric Voltages from 250 to 1000 V, while the shear rate up to 160 s^{-1}. In order to obtain reliable experimental data, measurements were repeated four or five times at the same operating conditions. These graphs present both Newtonian and Bingham property of the ER fluids and the effect of concentration of polarised particles together with the intensity of applied electric field on ER behaviour.

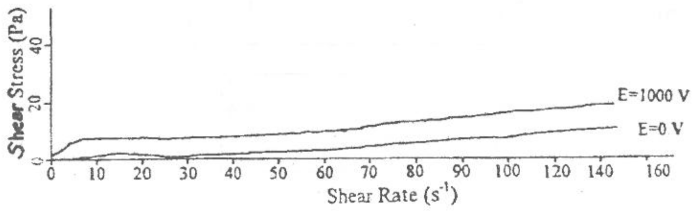


Figure 4. Viscous behaviour of mineral oil-based ER fluid containing 20% corn starch by weight.

Investigation of Figures 4 to 7 under the application of electric field show the effect of concentration of the corn starch on the shear stress. These curves reflect Bingham plastic characteristics, i.e. under an applied electric field flow only occurs for a stress greater than the yield stress. Application of 1 kV can cause an increase in yield stress approximately 6 Pa, 10 Pa, 18 Pa and 110 Pa corresponding to the weight ratios of 20%, 30%, 40% and 50% corn starch in mineral oil, respectively. It is clear that yield stress

Slopes of viscous behaviour curves for the mineral oil-corn starch ER fluid under the applied different electric fields are almost the same with the slope of curve for the ER fluid without no electric field applied. It can also be deducted from these curves that shear stress difference between with and without electric field does not change at any shear rate. It has a constant value which is approximately equal to the yield stress.

The slope of the flow curves indicate the Newtonian viscosity of mixtures. To validate the results obtained from Rotational viscometer, some are cross checked with the results obtained from a saybolt viscometer. It is seen that slope of the fluid under consideration is about 0.057 in Figure 4 and saybolt viscometer result is the 0.052 Pa.s. This difference may be emerged from the measurement errors and it may be tolerable according to the nature of the work, but nevertheless, a consistent method is set to determine viscous behaviour of ER fluids.

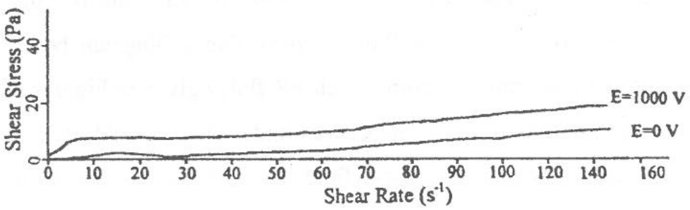


Figure 5. Viscous behaviour of mineral oil-based ER fluid containing 30% corn starch by weight.

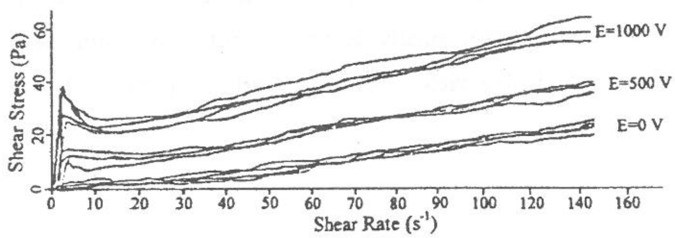


Figure 6. Viscous behaviour of mineral oil-based ER fluid containing 40% corn starch by weight.

Figures 6 and 7, depicting viscous behaviour under the electric field show humps within the small region of shear rate around 2 s^{-1}, where the fluid behaves as a solid. It is realised that the torque motor used to rotate the inner cylinder of the viscometer can not overcome the yield stress created by the ER fluid resistance and the bearing friction force. When the inner cylinder starts its motion initially formed chains break suddenly. This phenomenon causes a sudden change in shear stress. This region can be assumed as a transitional region and the results obtained within this small region should not be relied on. Figure 7 indicates also that with increasing the electric field, yield stress increases linearly. Obviously, there is a direct proportional relationship between them. Figures 8 to 11 show the mechanical stress/strain relationship for transformer oil-based ER fluids. These curves are obtained by using the same experimental set-up and measurement techniques.

The curves which are obtained under 0 V/mm electric field have Newtonian fluid characteristics. When the slope of this curves are investigated, it is seen that they are approximately the same with Saybolt viscometer measurements given in Figure 2.b. For example, Newtonian viscosity of the ER fluid which contains 30% corn starch and 70% Transformer oil is 0.02 Pa.s and the slope of the flow curve of this ER fluid is 0.02. Under the application of an electric field, these fluids behave like a Bingham body. When the viscous behaviour of transformer oil-corn starch ER fluids given in Figures 8 to 11 are examined, it is seen that the slopes of the curves under electric field are not parallel to the slopes of the curves without electrical field. It can be stated that shear stress difference between the with and without electric field is reduced by increasing the shear rate. At certain shear rate it would be very small or zero. The yield stress of the fluids in the same figures are 7, 18, 62 and 158 Pa for the weight ratios of 20, 30, 40 and 50% corn starch particle in transformer oil respectively. As in the case of mineral oil-starch ER fluid, yield stress increases exponentially depending on the concentration of corn starch in transformer oil. And also yield stress is linearly proportional to the applied electric field.

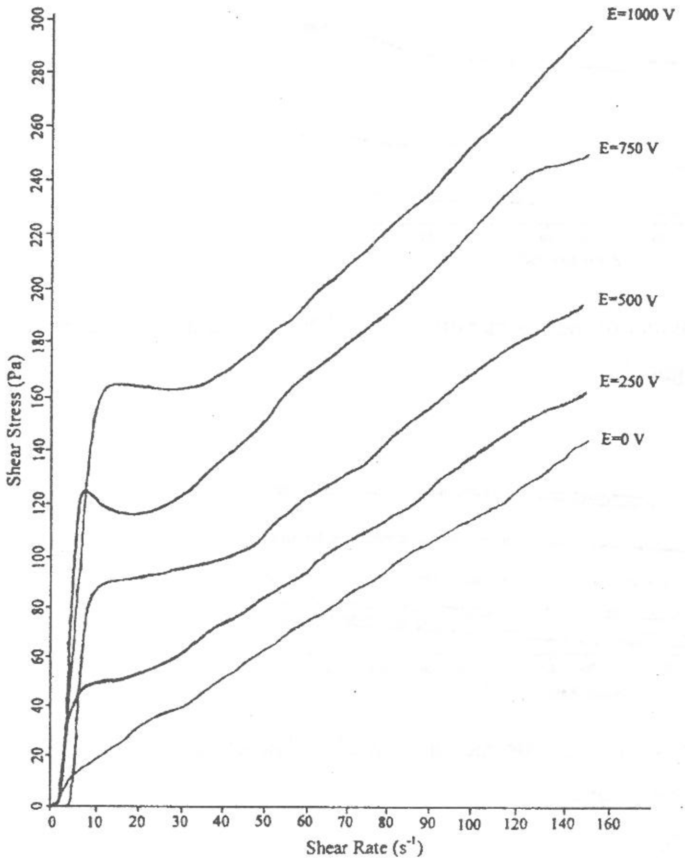


Figure 7. Viscous behaviour of mineral oil-based ER fluid containing 50% corn starch by weight.

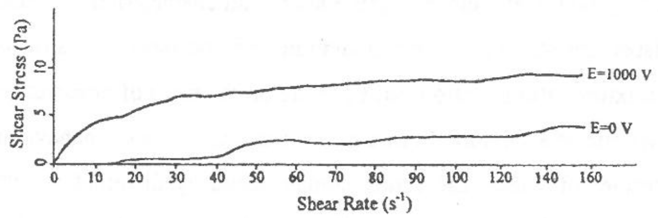


Figure 8. Viscous behaviour of transformer oil-based ER fluid containing 20% corn starch by weight.

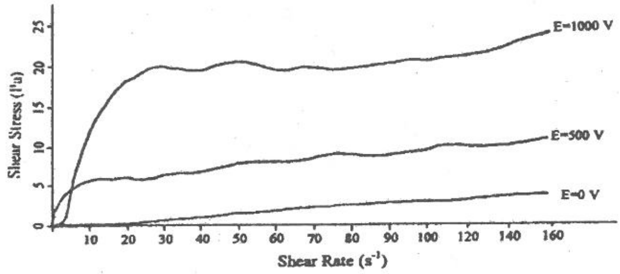


Figure 9. Viscous behaviour of transformer oil-based ER fluid containing 30% corn starch by weight.

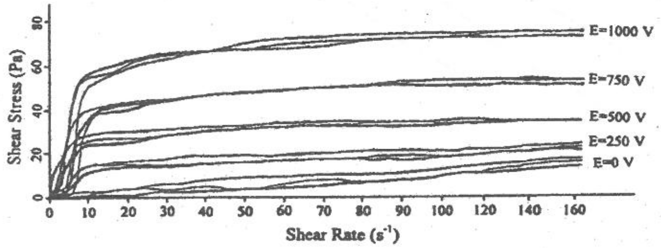


Figure 10. Viscous behaviour of transformer oil-based ER fluid containing 40% corn starch by weight.

IV. CONCLUSION

While designing an ER device, a common requirement is that the ER fluid have a high ratio between applied field shear stress and no-field shear stress. Power requirement and solid content of the ER fluids should be known before designing the ER devices. Since, they are important controlling factor of yield strength. Other fluid characteristics for the device design are the dispersion stability to sedimentation and no-field viscosity. A suitable base fluid and a mixture ratio selection can be made on the basis of observation of the rheological characteristic of a mixture. In this paper, electrorheological behaviour of mineral oil and tranformer oil based ER fluids contaminated by different weight ratios of corn starch were compared experimentally. The experimental results show that ER properties of the both base fluid under consideration are these:

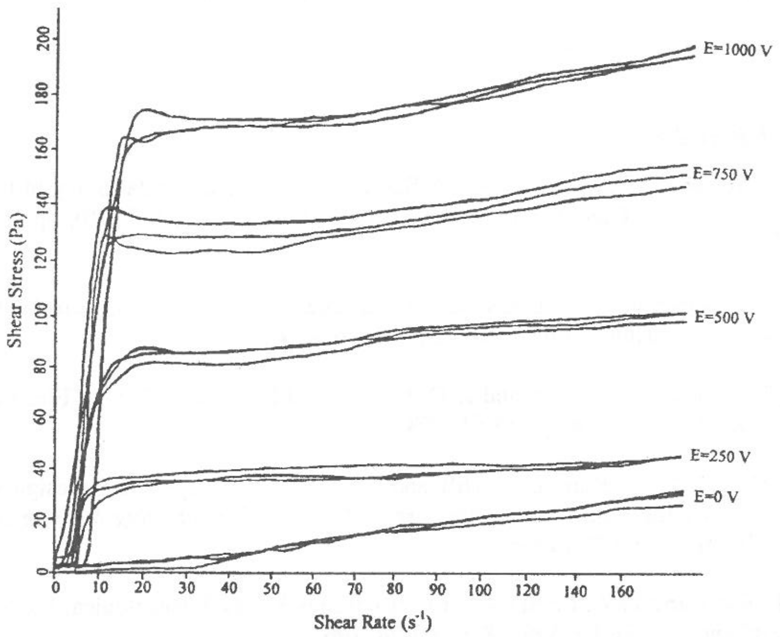


Figure 11. Viscous behaviour of transformer oil-based ER fluid containing 50% corn starch by weight.

- Yield stress increases linearly with increasing the electric field.
- Increase of concentration of dielectric particles causes the exponential yield stress increase.
- Newtonian viscosity exponentially increases with increasing the concentration of dielectric particles

Transformer oil-based ER fluid have some advantages over the mineral oil-based ER fluid. These are:

- Newtonian viscosity of the transformer oil-based ER fluid is low. Low no-field viscosity property of this fluid provides low pressure drop passing through an orifice.
- The sedimentation of the dielectric particles in transformer oil takes long time.
- Increase of yield stress of the transformer oil-based ER fluids under the applied electric field is always higher than mineral oil-based ER fluids yield stresses at all weight ratios.

One of the major disadvantage of the transformer oil is the decrease of the shear stress between the no-electrical field and under electrical field, while increasing the shear rate.

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