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Magnetorheological characterisation of carbonyl iron based suspension

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Materials

ABSTRACT

Purpose: The main aim of this article was to present the investigation results of magnetorheological fluids (MR) composed of carbonyl iron (CI) particles and analyse their flow behaviour in terms of the internal structure formation by a control of applied external magnetic field. The morphology, magnetic properties, sedimentation stability, and magnetorheological properties of the examined MR fluids were studied.

Design/methodology/approach: Model MR fluid was prepared using silicone oil OKS 1050 mixed with carbonyl iron powder CI. Furthermore, to reduce sedimentation Aerosil 200 was added as stabilizers. In the purpose to determine the properties of the analyzed fluids the sedimentation and dynamic viscosity were investigated.

Findings: Dynamic viscosity of investigated magnetorheological fluids rapidly and reversibly change in response to the applied external magnetic field. Moreover added particles of fumed silica inhibited sedimentation of carbonyl iron particles.

Research limitations/implications: MR fluids with excellent properties can be applied in various fields of civil engineering, safety engineering, transportation and life science. They offer an outstanding capability of active control of mechanical properties. But there are no systematic published studies of factors affecting the durability of MR fluids and devices. There is very little information on the effects of exposing different MR fluids to temperature, for this reasons further efforts are needed in order to obtain even better results.

Originality/value: The investigation results are reliable and could be very useful both for designers and the practitioners of many branches of industry.

Keywords: Smart materials; Magnetorheological materials; Carbonyl iron; Magnetorheological properties

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1. Introduction

Field responsive fluids include magnetorheological (MR) fluids, ferrofluids and electrorheological fluids. A common property of these materials is that, in most cases, they are all dispersions of particles in a carrier liquid and some aspect of their rheology is controlled by an external electric or magnetic field [1-3].

Typical magnetorheological fluids are the suspensions of micron sized, magnetizable particles (iron, iron oxide, iron nitride, iron carbide, reduced carbonyl iron, unreduced carbonyl iron, chromium dioxide, low-carbon steel, silicon steel, nickel, cobalt, and combinations thereof [4]) suspended in an appropriate carrier liquid such as mineral oil, synthetic oil, water or ethylene glycol. The carrier fluid serves as a dispersed medium and ensures the homogeneity of particles in the fluid [5]. Typically, the diameter of the magnetizable particles range from 3 to 5 microns [6,7].

A key to the magnetorheological response of MR fluids lies in the fact that the polarisation induced in the suspended particles by application of an external magnetic field. The interaction between the resulting induced dipoles causes the particles to form columnar structures, parallel to the applied field, as shown in Figure 1 [8]. These chain-like structures restrict the motion of the fluid hence increase the viscous characteristics of the suspension.

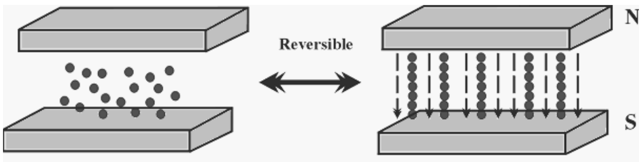

Fig. 1. Micro-structures of MR fluids without/with external magnetic field [8]

In essence, MR fluid behaviour transforms from that of a liquid to that of a solid-like gel when an external magnetic field is applied. The dramatic transformation of MR fluids can be quite fast, on the order of 10-3 and 10-4 seconds, therefore, the MR fluids can be used as actuators in various damping schemes [9].

The ability to change the yield strength of MR fluids according to the magnetic field enables MR fluids to alter the structural damping and stiffness coefficients, therefore to make the structure "smart" or "intelligent" [7,10].

The properties of magnetorheological (MR) fluids allow their use in many commercially available products.

Examples include small, linear dampers for real-time [11,12], semi-active vibration control in vehicles, rotary brakes [13], large linear dampers for semi-active control of seismic motions in buildings and bridges, magnetic abrasive flow machining, magnetic float polishing [14,15] and special purpose devices for rehabilitation process support [16].

2. Experimental

Carbonyl iron powder was selected (CI, reduced penta-carbonyl iron, SiO_2 - coated, BASF, Germany) as for a model particle suspended system. This is because carbonyl iron is magnetically soft material and characterize by high saturation magnetization. The average particle size and tap density are 6.0-8.0 μm and 4.3 g/cm^3, respectively.

The concentration of CI was fixed at 20 and 40 wt%. To reduce sedimentation of the CI particles additional components (1 against CI amount) were added to the fluids. For the silicon oil the fumed silica (Aerosil 200, Degussa, Germany) was chosen.

Composition of the prepared MR fluids is listed in Table 1.

Table 1.
Composition of the investigated magnetorheological fluids

Carrier oil	CI content [wt %]	Additive Type	Additive Amount [wt % of CI]
OKS 1050 50 mPa·s	20	Aerosil 200	1
	40		1
OKS 1050 500 mPa·s	20	Aerosil 200	1
	40		1

The function of a carrier liquid is primarily to provide a liquid in which the magnetically active phase particulates are suspended.

The carrier liquid should also be largely non-reactive towards the magnetic particles. Similarly, the carrier liquid should be non-reactive toward the components/materials used in the device.

When selecting a carrier liquid, it is important to consider the boiling temperature, vapour pressure at elevated temperatures and freezing point.

For that reasons magnetorheological particles were dispersed in colorless silicone oil (SO, type OKS, Germany).

Magnetorheological characteristics were examined using laboratory test stand, which could work as viscometer or it could perform a function of laboratory clutch (Figure 2).

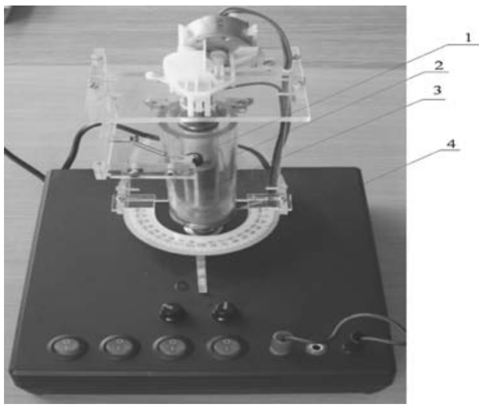

Fig. 2. Apparatus for MR effect measurement. 1 - shaft (drive) and inner cylinder, 2 - outer cylinder, 3 - coil, 4 - needle and angular displacement scale

A drum (1) is immersed in magnetorheological fluid and rotates driven by drive. Current supplied to the coil (3) generates magnetic field that increases viscosity of the MR fluid. By increasing voltage supplied to the coil, the change in MR fluid viscosity was observed. The applied torque is transferred from an inner drum (1) to the movable outer cylindrical vessel (2). A spring stops the outer cylinder movement and shifts the needle to the appropriate position on the angular displacement scale (4). The voltage was changed gradually from 1.25 up to 6 V in 0.5 V steps. Each measurement was repeated three times and the average value was taken.

The sedimentation was measured by visual observation of the position changes of boundary between clear and turbid part of carrier oil at room temperature [4].

Prepared samples were placed into cylindrical glass test tubes (length 1 m, diameter 30 mm) for a few days.

Sedimentation ratio can be calculated by formula (1):

$$R = \frac{b}{(a+b)} \cdot 100\% \tag{1}$$

where:
a - the length of the clear fluid,
b - the length of the turbid fluid.

The coil current and magnetic field strength were controlled using a separate control unit.

Metallographic examinations of the material structure and its chemical composition were made on the XL-30 PHILIPS scanning electron microscope with EDAX energy dispersion X-ray spectrometer with 20 kV accelerating voltage.

3. Results and discussion

The observations of the carbonyl iron CI and applied stabiliser of the magnetorheological fluid - silica (Aerosil 200) were conducted within the of microscopic investigations in the scanning electron microscope.

Figure 3 shows characteristic morphologies of CI by the SEM. The carbonyl iron particles possess in general spherical shape with a size distribution.

Initially constructed chain structure of these particles can be transformed into an assembled structure of individual chains through the chain rupture and reformation process by shear deformation under an applied magnetic field.

Additionally, in order to confirm high purity of the carbonyl iron used to prepare MR fluids, the investigations of the chemical composition were made (Figure 4). The surface of CI is coated of the silica dioxide layer with the purpose of avoidance carbonyl iron particles agglomeration.

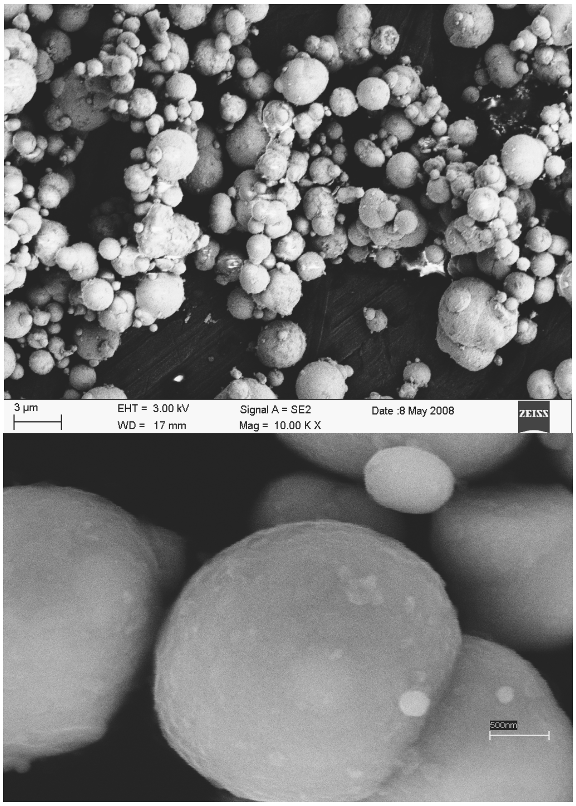

Fig. 3. Scanning electron micrograph of carbonyl iron particles used to prepare MR fluids. Magnification 10 000x and 75 000x

It was found on the basis of conducted observations that analysed silica was characterized by irregular shape (Figure 5). The silica surrounds the spherical particles of the iron, preventing the same their agglomerations in the suspension.

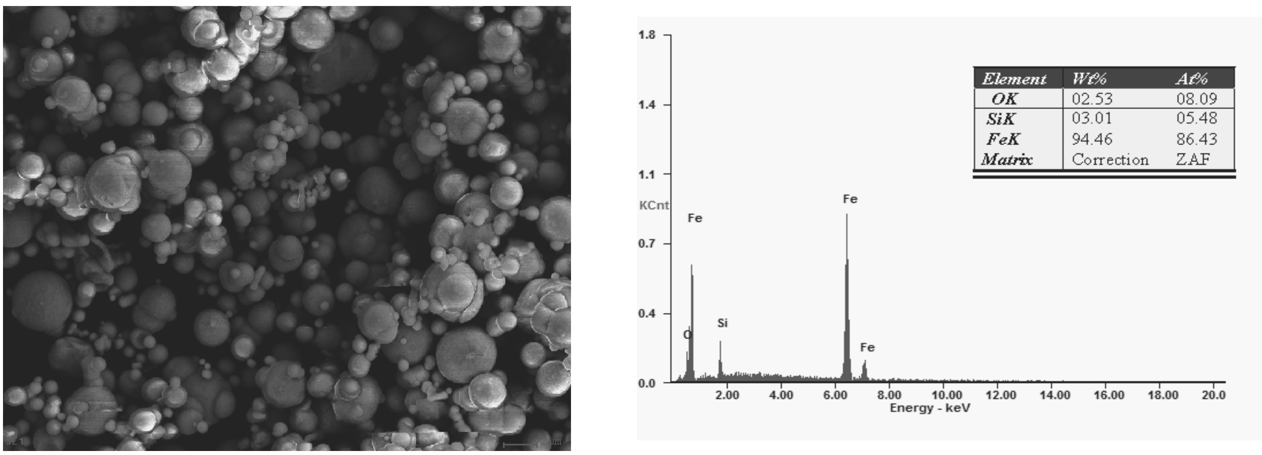

Fig. 4. SEM morphology and special pointwise microanalysis of the chemical composition of the carbonyl iron

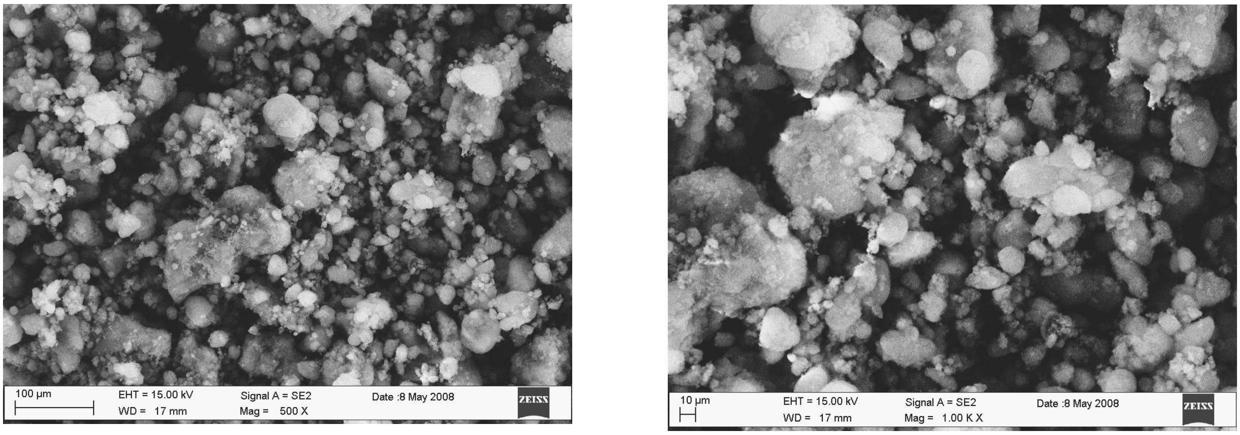

Fig. 5. Silicon dioxide (Aerosil 200)

In order to confirm the chemical composition of used silica the X-ray microanalysis was executed moreover, using EDAX energy dispersion X-ray spectrometer with 20 kV accelerating voltage. The results of the chemical composition of the analysed silica are presented on the Figure 6.

The effect of additives on the stability of the magnetorheological fluid has been investigated experimentally. The filled MR fluids having different compositions were set in a static condition, until it reached asymptotic values.

Analyzes the liquid MR about viscosity 50 mPa·s and concentration of carbonyl iron 40%, investigation showed slow decrease of the sedimentation coefficient in the case of the fluid with and without the silica (Figure 7).

It was also noticed that stability of investigated fluids improves after adding the stabilizer.

This is the effect of the silica gel arising net, which prevents agglomeration of the carbonyl iron particles and the same descent of the agglomerates on the bottom of the reservoir.

The liquid MR about viscosity 500 mPa·s and CI 40% characterizes the largest stability from among studied liquids.

The value of the sedimentation coefficient contain in the range 93 -95% after 30 h of the descent (Figure 8).

In order to state the influence of the stabilizer the sedimentation process should be prolonged to 60 h.

The main aim of the investigations was the qualification of the influence of external magnetic field on the dynamic viscosity of the prototype magnetorheological fluid.

For this reason under consideration were taken following factors: concentration of magnetic particles (carbonyl iron), viscosity of the carrier liquid and influence of applied stabilizer (Aerosil 200).

It was affirmed on the basis of conducted investigations that with the enlargement of the concentration of magnetic particles (CI) increase the dynamic viscosity of analysed liquids together with the extension of the intensity of the external magnetic field.

Higher content of CI increase also the stability of the investigated fluids. The values of the dynamic viscosity increase up to 21 $kg/m{\cdot}s^2$ in the case of the MR fluid (OKS 1050, 50 mPa·s), while the dynamic viscosity of the MR fluid (OKS 1050, 500 mPa·s) was on the level 26 $kg/m{\cdot}s^2$

The relationship between the dynamic viscosity of MR fluids and the intensity of the external magnetic field is shown on Figures 9 and 10.

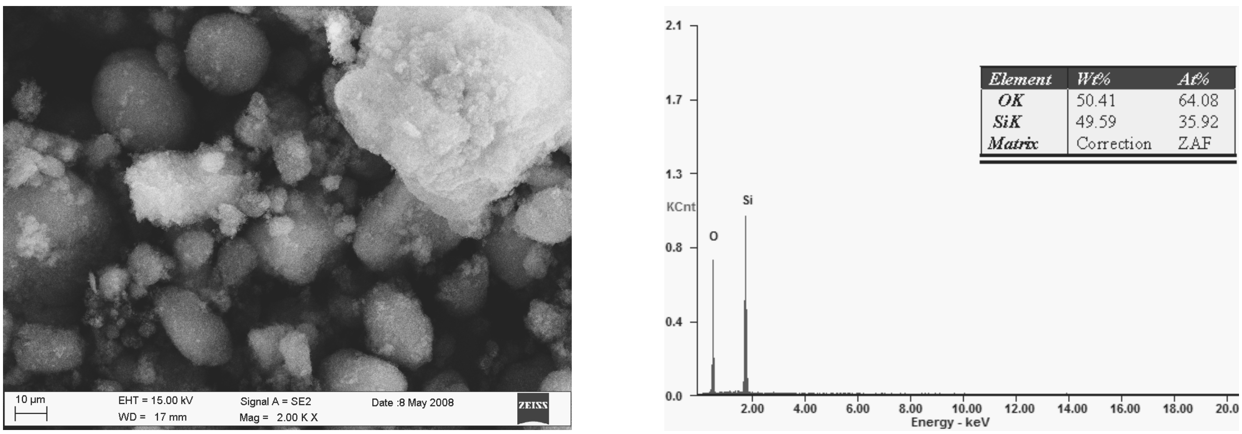

Fig. 6. SEM morphology and special pointwise microanalysis of the chemical composition of fumed silica (Aerosil 200)

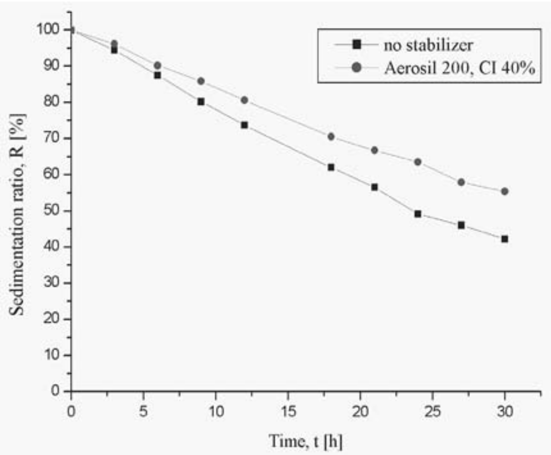

Fig. 7. Sedimentation ratio R of MR fluid (OKS 1050, 50 mPa·s)

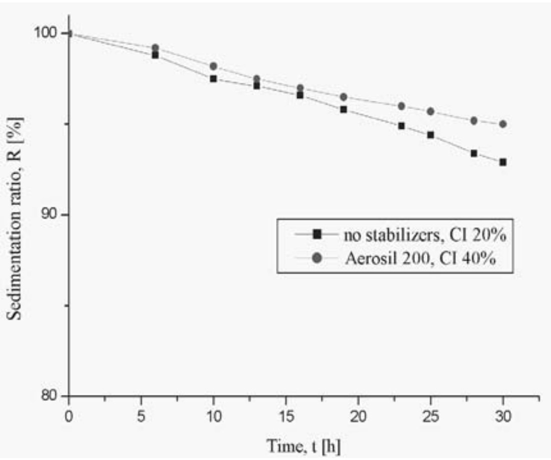

Fig. 8. Sedimentation ratio R of MR fluid (OKS 1050,500 mPa·s)

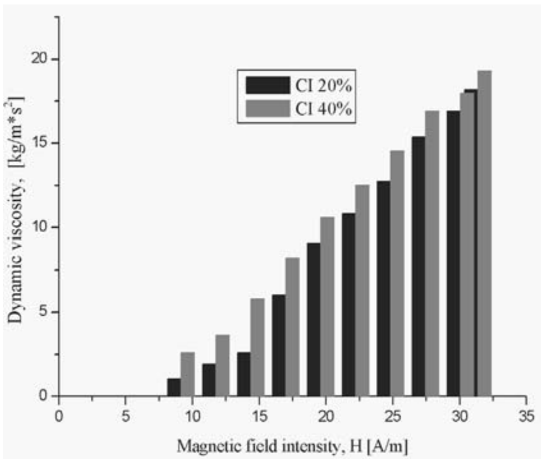

Fig. 9. Dependence of MR fluid (OKS 1050, 50 mPa·s) dynamic viscosity on the magnetic field intensity

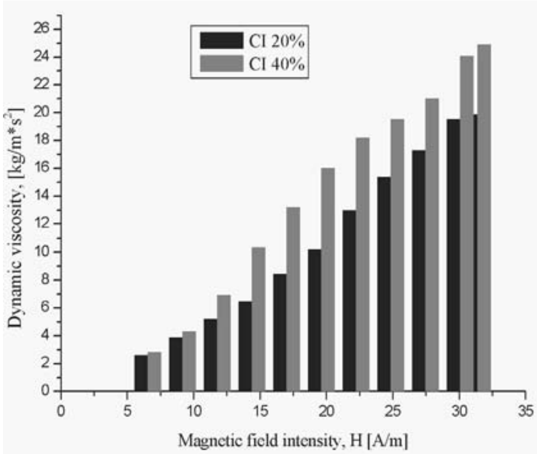

Fig. 10. Dependence of MR fluid (OKS 1050, 500 mPa·s) dynamic viscosity on the magnetic field intensity

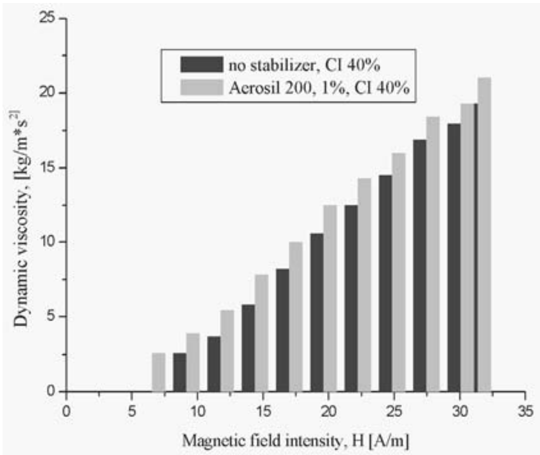

Fig. 11. The influence of the stabilizer on the dynamic viscosity of MR fluid (OKS 1050, 50 mPa·s)

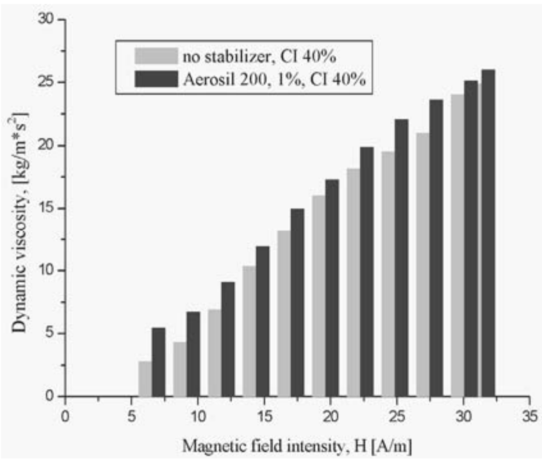

Fig. 12. The influence of the stabilizer on the dynamic viscosity of MR fluid (OKS 1050, 500 mPa·s)

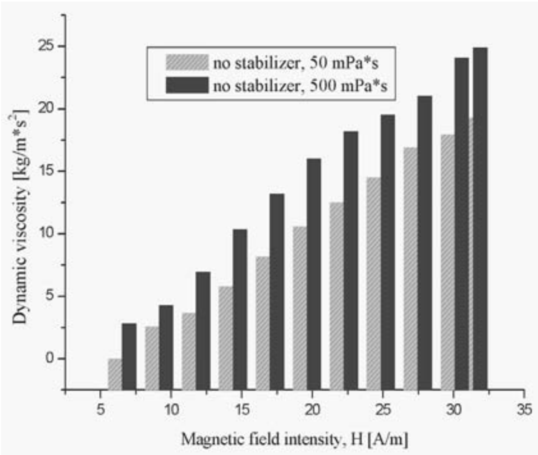

Fig. 13. The influence of carrier liquid viscosity on the dynamic viscosity of MR fluid (CI 40%)

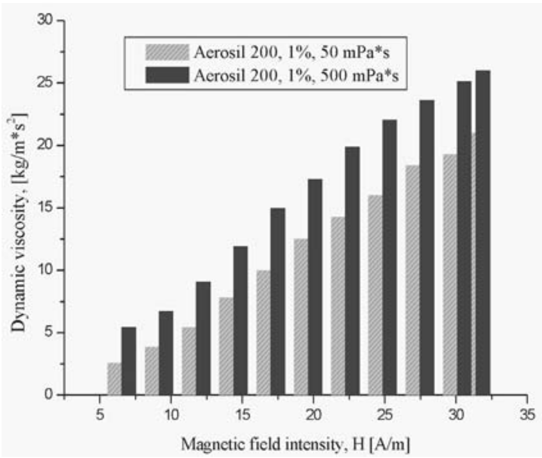

Fig. 14. The influence of carrier liquid viscosity on the dynamic viscosity of MR fluid (CI 40%)

The most important for the magnetorheological properties is presence of the stabilizing additives which further increase the MR effect. Besides that in the presence of stabilizers MR fluid are more homogeneous and faster respond to the external magnetic field at lower magnetic field intensity.

It was affirmed on the basis of experimental results that the dynamic viscosity of studied liquids increase with enlargement of the intensity of the external magnetic field after the addition of silica considerably (Figure 11 and 12).

This is caused that added silica prevents concentrating of the CI particles as a result of the gel mesh formation.

For this reason the particles of the iron slowly fall on the bottom of the drum and larger quantity of magnetic particles has been still subjected to the applied external magnetic field.

As shown on Figure 13 and 14, generally dynamic viscosity of MR fluid increase with increasing of oil viscosity, both for non stabilized suspension and with fumed silica addition.

4. Conclusions

On the basis of conducted investigations following conclusions were formulated:

1. With the increase of the carrier liquid viscosity and carbonyl iron particles concentration the analysed magnetorheological fluids exhibit high stability in the course of time.
2. Added submicron-sized particles (fumed silica) in 1% with relation to CI amount further inhibited sedimentation of the carbonyl iron particles especially effective for high loaded (40 %) MR fluid.
3. The dynamic viscosity of investigated magnetorheological fluids increase in the response to presence of an external magnetic field:
   - with the amount of CI and augmentation of the carrier liquid viscosity,
   - presence of the stabilizer additive (Aerosil 200).

Acknowledgements

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