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Magneto-rheological defects and failures: A review

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Abstract. Magneto-rheological fluid is the colloidal suspension of micron sized magnetic particles in a carrier fluid where defects and failures occur at many circumstances. This paper presents a review on defects and failures of magneto-rheological fluid in engineering applications. The most significant defect is hard cake which developed due to re-dispersion difficulties of remnant particles magnetization, leaving the magneto-rheological fluid ineffective. Clumping effect on the other hand is a separation of carrier fluid from the magnetic particles when magneto-rheological fluid is being exposed to higher magnetic field for an extended period of time. As clumping occurred, it leads to Fluid Particle Separation (FPS) which is believed altering the strength distribution of magneto-rheological fluid and therefore reducing the squeezing force. Another significant failure is magnetic particles oxidation of the magneto-rheological fluid. This paper also will discuss on stability problems which is the most challenged issue in magneto-rheological fluid technology. With the comprehensive review in this paper, researcher can design materials of magneto-rheological fluid for better properties.

1. Magneto-Rheological Fluid

Magneto-rheological fluids are a kind of smart materials whose viscosity can be changed using an external magnetic field. The viscosity changes of magneto-rheological fluids altering the fluid shear stress in a function of magnetic field strength. In previous study, magneto-rheological fluids were applied in various engineering devices such as damper, clutches, brakes and valves. Magneto-rheological fluid damper also used in civil structure for mitigating seismic vibration. After more than two decades of research works (1990-2010), researchers around the world start to extend the magneto-rheological fluid technology to a new application. However, magneto-rheological fluid reported to have some limitations that reduce its ability to extend the application. Failures and defects such as hard cake, clumping effects, fluid particles separation (FPS) and particles oxidation require special attention to minimize the effects on magneto-rheological fluid. Stability, which involves the problem of particles sedimentation and settling rates also need to be improved.

2. Defects and failures of Magneto-rheological fluid

Align with continues development of magnetic fluid technology, the study of magneto-rheological fluid are gradually expand. Researchers are exploring new ways to produce high performance of the fluid. The development of new materials with new formation of applications however needs improvements in terms of the defects and failure.

2.1 Hard cake

From years to years, a lot of novel magneto-rheological fluid compositions been developed. In the absence of particular additives, most magneto-rheological fluid faced problems due to sedimentations and the formation of hard cake. The tightly hard cake is extremely hard to re-disperse due to strong aggregation and the remnant magnetization between the particles, which are not vanished even without magnetic field application. [1] However, selection of suitable additives in magneto-rheological fluid composition is also important. On 2006, López-López et al. worked on the re-disperse ability of concentrated iron-based magneto-rheological fluid containing several surfactants in both on-state and off-state. The addition of silica nano-particles as surfactant was found to avoid particle settling during off-state, but the thixotropic silica gel is rapidly broken during on-state. This phenomenon allows the iron particles to settle down and formed a hard cake that is very hard to re-disperse. [2]

On 2013, Powell LA et.al discovered hard cake during synthesized magneto-rheological fluid for helicopter landing gear application. They described hard cake as a formation due to the ineffective magneto-rheological fluid resulted from the re-dispersion problem. Therefore, surfactant, such as lecithin, was suggested to improve mix-ability of the magneto-rheological fluid. This is believed will decrease the permeability of the fluid and therefore reduces the settling rates of the particles. [3]

Besides adding surfactants, applying coating to the iron particles had also been studied. One of coating materials applied by researcher was polyvinyl-butyral (PVB). Jang et.al investigated the rheological properties and dispersion stability of magneto-rheological fluid with PVB coating and compared the sedimentation characteristic with the un-coated carbonyl iron particles. The result showed the PVB coated improves sedimentation behavior with a decreased particle density. The PVB coating was preventing the hard cake formation among the carbonyl iron particles, reduces rusting of CI particles, and also protects the device from abrasion. [4]

Another modern investigation to improve stability of magneto-rheological fluids was done by Iglesias et al. Instead of adding surfactant or stabilizer, they introduced small amount of magnetic nano-particles (up to 3vol%) to a suspension of micro-particles (32vol %). This method successfully avoids the hard cake formation and formed a stable magneto-rheological fluid. Furthermore, the fluid easily re-dispersed and the yield stress was found to be strongly field dependent.[5]

2.2 Clumping Effect

Clumping effects have been discovered by several researchers before. Farjoud et.al discovered this phenomenon upon constructed a rheometer that functional for testing magneto-rheological fluids behavior by means of dissimilar parameters. They did modeling and testing magneto-rheological fluids in squeeze mode, enhancing an idea to design magneto-rheological devices. Result of the testing showed trapped iron particles in the forming chains of magnetic field even though the carrier fluid can flow freely. As the test repeated for few times, the total iron particles trapped in the gap became higher. However, most of the carrier fluid left the gap and leaves the particles behind. [6, 7]

A Study on the Dynamic Characterization of a Tunable Magneto-Rheological Fluid-Elastic Mount in Squeeze Mode Vibration was done in 2011 by Adjerid K. Even though the result of this study deviated by nearly 22 percent after several cycles, the phenomenon of clumping effect was observed and been studied. Fundamentally, this clumping effect occurs when higher magnetic field is applied to the magneto-rheological fluid for a longer period of time. As the clumping becomes apparent, the carbonyl iron particles in the magneto-rheological fluid become entrapped in the chains that were formed under magnetic field. In this study, it is clearly showed that the clumping effect occur due to the rapid increments of both force and displacement transmission through the carrier fluid. Therefore, the magneto-rheological fluids become stiffer and have higher damping values. [8] Figure 1 shows the clumping process throughout three cycles of test.

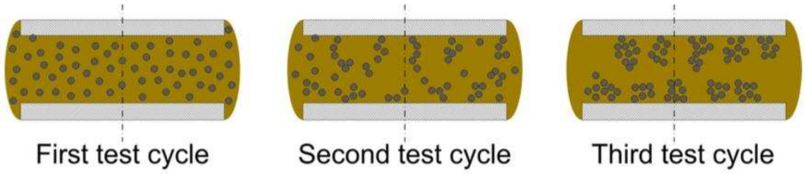

Figure 1. Clumping process throughout three cycles of test [8]

The clumping effect may be a simple problem in certain magneto-rheological research study and testing. However it may become worst when the problem affected the application itself. Exemplary, can be seen in damper application. There was a study on biviscosity model, by Huang et.al in 2011 to explain the constitutive characteristics of magneto-rheological fluids with an application of magnetic field of the magneto-rheological isolating damper. As depicted in Figure 2, the squeezing force seems to be 216kN in the absence of magnetic field. However, magnetic field of 50 kAmp/m, 100 kAmp/m, and 200 kAmp/m resulting the forces at 250 kN, 278 kN, and 302 kN respectively.

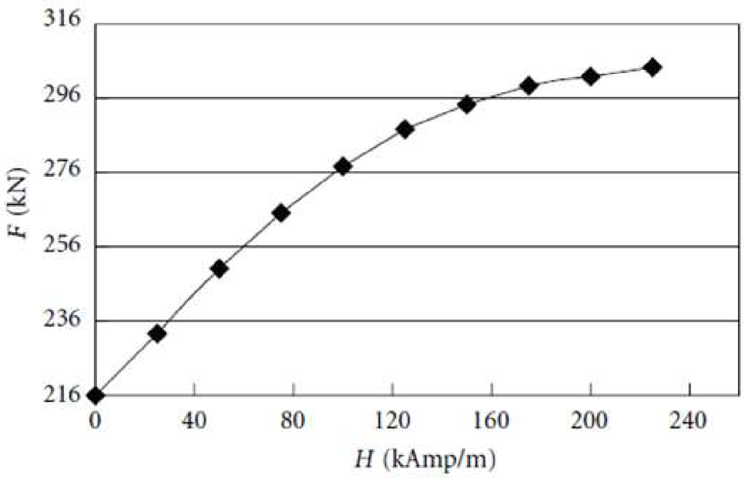

Figure 2. Squeezing force vs magnetic field strength of Magneto-rheological fluids [9]

The results clearly show that the squeezing force is increases as the velocity and the applied magnetic field increase.[9] However, this result will not be achieved if the clumping effect occurs to the magneto-rheological fluid. The required squeezing force will not be increase as the magnetic field increases and will then limiting the applications of the damper.

2.3 Fluid Particle Separation (FPS)

In magneto-rheological fluid, clumping problem links to another phenomenon so called Fluid Particle Separation (FPS). FPS referred to complex environment of magneto-rheological fluid occurs in squeeze mode. It was believed by researchers as something that difficult to study. Ismail.I et.al was successfully investigated the relationship between FPS and mechanical behavior of magneto-rheological fluid throughout compression in squeeze mode. This investigation was done by means of cyclic compression tests and video recording on the forced out fluid. Separation of carrier fluid and iron particles was observed when magneto-rheological fluid being compressed between two parallel plates. The phase separation of the fluid was observed. Aggregations of the particles also were produced. Besides, resistance to compressive motion was increased. Therefore, FPS phenomenon occurred due to pressure build up, magnetic field distribution and changes of particles chain structure. [10, 11]

Fluid Particle Separation (FPS) is believed altering the strength distribution of magneto-rheological fluid and therefore reducing the squeezing force. This observed clearly when dealing with compression stress, where the magneto-rheological fluid behaves unique behavior with its own stress strain curve. With three phases existed during the compression, this magneto-rheological fluid shows different characteristics in each phase. The stress strain relationship of magneto-rheological fluid as depicted in Figure 3 was studied by Mazlan et al. [12]

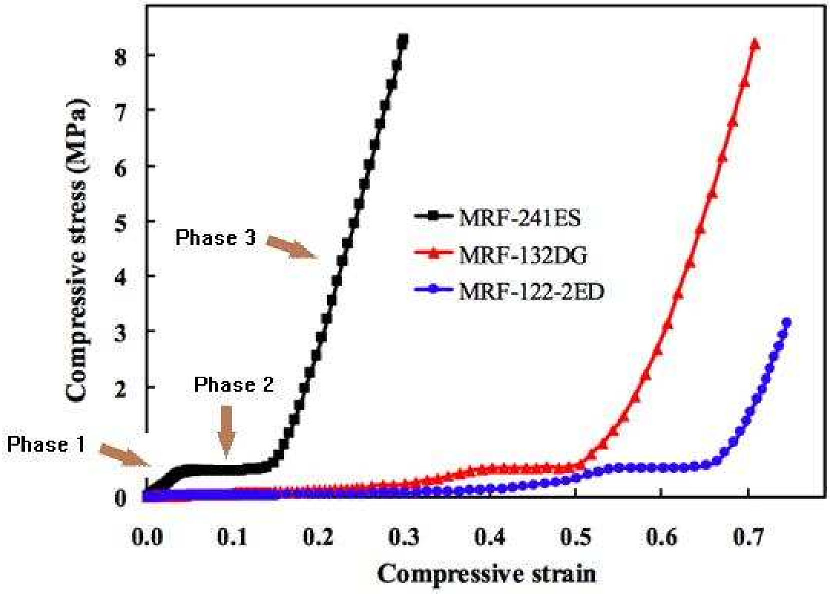

Figure 3. Stress-strain relationships of compression test [12]

At Phase 1, the stress strain curve illustrated comparable pattern to any solid materials under compression. This influenced by action between magnetic particles and carrier fluid. They co-operated together like alloy or composite as a single material. At phase 2, stress strain curves bear a resemblance to the entire process between the dealings of carrier fluid and magnetic particles to survive to the forces and carrier fluid movement. Here, the particles and carrier fluid are in progress to break up because of the movement flow. The carrier fluid flow away from the compression area and separated with magnetic particles. Lastly, a new structure with full of particles appeared at phase 3. This three phases curve represents a new structure that has a better resistance to compression forces. [12]

2.4 Oxidation of particles

Magnetic particles, in magneto-rheological fluid are normally consist of 20-40% by volume. Suspended in various types of carrier fluid, particles can be carbonyl iron, stainless steel flakes, hydrogen reduced iron, and magnetic iron oxides. However, most frequently used material of magnetic particles in magneto-rheological fluid is carbonyl iron powder (CIP) with iron content of 97–99 % [13] Magnetic particles which are iron based particles always faced to some challenges in magneto-rheological fluid technologies. Once expose to atmosphere, either spontaneously or in operating at high temperatures, oxidation of the particles will lead to lesser the magnetizing ability of the particles. Therefore, the magneto-rheological effect will be diminished.[14]

In addition, oxidation problem also caused from the instable magneto-rheological fluid. Particles oxidation leads to increase the off-state viscosity of the magneto-rheological fluid over time. Besides, devices failures might occur. Perhaps, an unmanageable paste magneto-rheological fluid will be. The will be increased in off-state viscosity because of the increased in solid volume. The action between small particles might also generate colloidal forces of the magneto-rheological fluid.[15]

Sunkara S et.al did a study on the particles oxidation within magneto-rheological fluid and its impact on the field-induced rheological properties. The experiment was done by oxidizing the iron particles in a controlled environment. The results were then compared to the model of dipolar magnetized particles. As shown in Figure 4, the oxygen content (10 vol% iron suspensions) developed a linear curve as the oxidation reaction time extended. This suggested the oxidation of iron particles growth linearly for 20 hours reaction time. Therefore it is believed that a non-adherent layer of oxide formed around the spherical iron particles.[16]

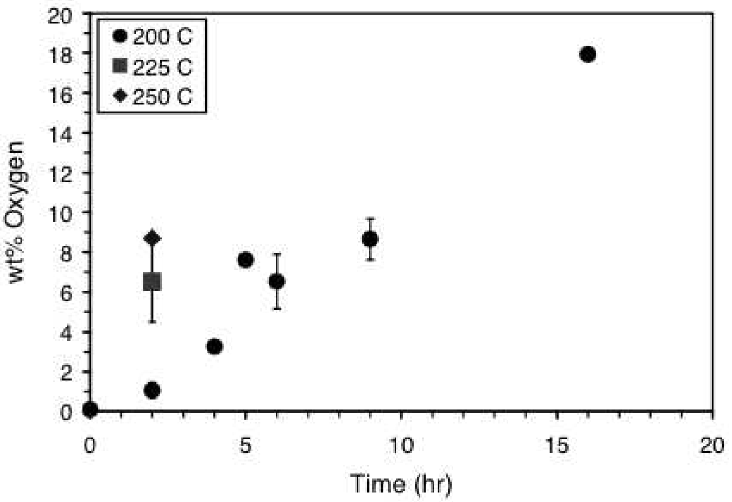

Figure 4. Oxygen content (10 vol% iron suspensions) versus oxidation reaction time.[16]

Oxidation of particle may lead to chemical changes of the iron which will disturb the performance of the magneto-rheological fluid in its application. A durability test of magneto-rheological fan clutch has been conducted for 540 and 108 hours of service and been compared with unused materials to study the particles oxidation process and its effect to the clutch. The result indicated that crystalline magnetites were produced and this may lead the gradual loss of fan clutch torque capacity especially for 540 hours durability test. Production of porous layer of magnetite on the particles surface proved that the iron particles oxides over time [17]. This result was supported by Roupec J et.all in the experiment of an automotive MR damper. Under the exposure to a long term loading simultaneously, the yield stress increases up to five times in the fluid off-state due to *in-use-thickening (IUT)*. The same increase was identified in the on-state. These results prove that a measurable decrease of magneo-rheological effect during the long term operation due to the degradation of magnetic properties which resulted from particles oxidation. [18]

2.5 Stability

Sedimentation stability is the gravitational stability that guarantees the particles have enough time to settle down. Agglomerative stability on the other hand avoids the particles from attach together in the lack of the magnetic field. Magneto-rheological fluid which consists of three elements with difference in size and density segregate and create areas of different composition during sedimentation.[19]

The sedimentation stability problems of Magneto-rheological fluids had been the focus of attention in practical applications. Magneto-rheological fluids should be required not only good magnetic rheological properties, but also possess a better stability. The issue of sedimentation stability affects the performance of the Magneto-rheological fluids, which will affects the development of Magneto-rheological fluids, to a certain extent, delay the development of industry. Under the zero-field strength, the magnetic particles will make a relative motion easily, duo to great different density between the magnetic particles and carrier fluid. Magnetic particles make a settlement under the action of gravity field. The molecules of carrier fluid will make a strike to magnetic particles in the role of Brownian motion, which may cause a certain degree of influence on the settlement. And the force between the magnetic particles will also influence the settlement of Magneto-rheological fluids. [20] To improve the stability of Magneto-rheological fluids from sedimentation problems, a choice of solutions were proposed in relation to their composition and the typical size of the magnetic part.

Sedimentation can be influenced by temperature and surfactant concentration. This were proved by K.Prekas et.al [21] on their study of Electro-rheological fluid (ERF). The study proved that increasing the temperature has a negative effect on the stability of the ERFs towards its sedimentation as depicted in Figure 5.

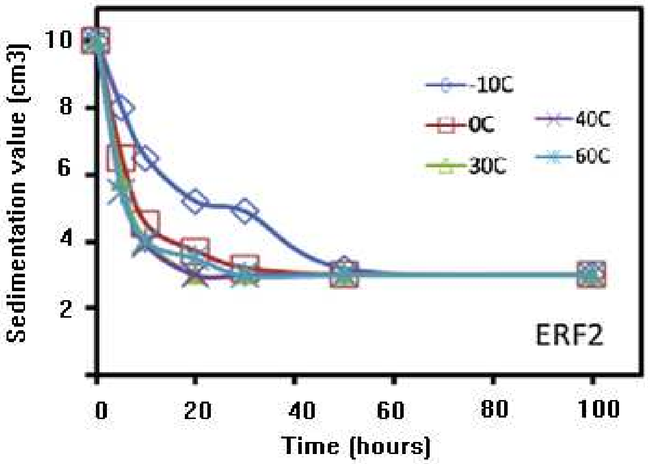

Figure 5. Effect of temperature on the sedimentation stability[21]

There was a further investigation on stability properties of the suspensions of carbonyl iron micro-particle in silicone oil at various temperatures. The results showed that adding 3 wt% of stearic acid to the magneto-rheological fluid resulted in 92% stability enhancement of the suspension even over a period of a month. The stability is eight times more compared to common magneto-rheological fluid. it can be conclude that at higher temperature, sample with additives were affected more than the other samples due to the fact that the base fluid is independent of temperature [22]

A recent reviewed enlightened some stabilization methods that been introduced by researchers. There are various methods have been proposed and used by researchers to improve the stability of these fluids[23, 20]. Magnetic particles coating[24-27], using nano-wires[28], using nano-spherical particles[29], combining magneto-rheological fluids and ferrofluids, introducing stabilizer additives[30-32], applications of gels[33] or other polymeric liquids as the base fluid are all the techniques to improve stability. Among the mentioned techniques, magnetic particles coating, stabilizer additives and nano-spherical particles are the most popular and noticeable methods.

An investigation of the magneto-rheological fluid response to applied magnetic field and the stability of the fluids have been done experimentally in 2006 by Kciuk and Turczy, as depicted in Figure 6.

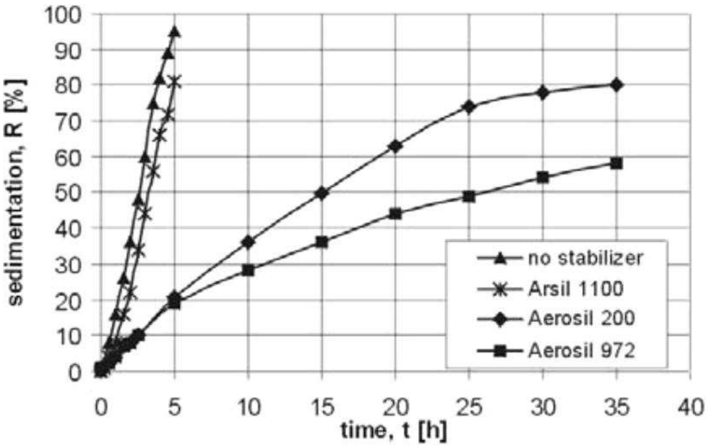

Figure 6. Sedimentation ratio vs time for Magneto-rheological fluid with different stabilizer [34]

Difference type of additives was added to the magneto-rheological fluid in order to improve the stability. As the result, stability of prepared Magneto-rheological fluids was different in each case. Additions of stabilization agents enhance the stability of the fluid based on types of stabilizer. As can see on Figure 6, addition of Arsil 1100 does not give good impact to the Magneto-rheological fluid. The fluid behaves similar to original magneto-rheological fluid. However, addition or Aerosil 200 and Aerosil 972 showed excellence stability. [34]

The study by K.Prekas et.al also proved that stability of the ERF suspension was better with addition of surfactant. Besides, it also leads to the enhancement of the ERF effect as depicted in Figure 7. This confirmed by addition of 1% surfactant concentration, there virtually no sedimentation of the suspended particles was observed after 30h. This was believed that the addition of surfactant to the ERF suspension enhances the particle interaction at the oil-particle interface and also leads to inter-particle repulsive forces. This then slow down the agglomeration process of particles and reducing the tendency of sedimentation. [21]

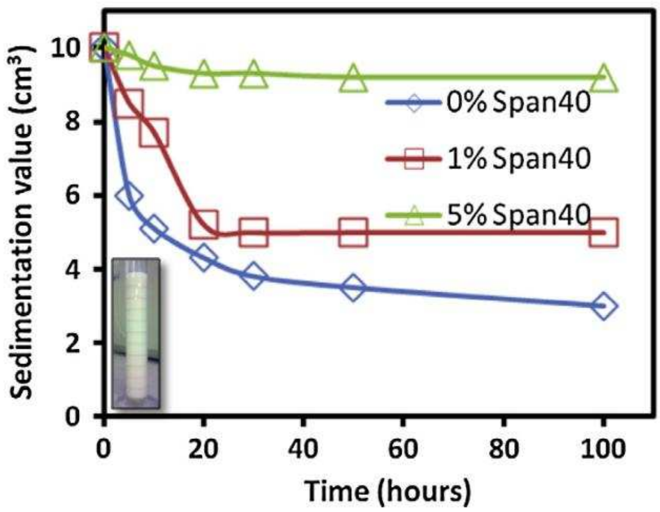

Figure 7. Effect of surfactant concentration on sedimentation stability [21]

Researcher also worked and prepared magneto-rheological fluids with different additive percentage to investigate the particle size and the rheological properties of the Magneto-rheological suspensions under applied magnetic strengths .The sedimentation effect of Magneto-rheological fluids is also studied. It is proved that the fluid exhibit non-Newtonian fluid in the absence of magnetic field. It is also observed that the sedimentation is improved by adding higher percentage of additives. [35]

Study on the effect of three different additives (oleic acid, aluminum stearate, and silica nano-particles) on the aggregation, sedimentation, and re-dispersibility of concentrated iron based magneto-rheological fluids was studied on 2006. By means of theological measurements, the re-dispersibility was studied both in the presence and in the absence of external magnetic field. It was found that although particle settling cannot be avoided by the addition of oleic acid or aluminum stearate, the re-dispersibility of the suspensions is considerably enhanced. Besides, the silica nano-particles behave like a gel-forming agent and able to prevent particle settling under rest conditions. Unfortunately, when iron-silica suspensions are sheared, compact sediments are progressively formed, making the re-dispersion extremely difficult. [36]

Stability of magneto-rheological fluid can also be improved by introducing single-walled carbon nanotube (SWNT). Fang et.al on 2007 proved by SEM images that the submicron-sized SWNT filled the interspaces among CI particles and prevent serious sedimentation problem. Addition small amount of SWNT was found to improve the uniform dispersion while sedimentation rate of the suspension also been reduced without affecting the yield behavior of the magneto-rheological fluid. [37]

However, to reduced the cost, Zhang et. al introduced a plate-like graphene oxide (GO) as the gap-filler to improve the sedimentation problem of carbonyl iron-based magneto-rheological fluid. Different weight ratios of GO and CI-GO were compared and the result showed that CI-GO mixture-based magneto-rheological fluid exhibited similar MR effects compared to that of a pure CI particle-based magneto-rheological fluid. The dispersion stability was also improved as amount of GO additive increase. [38]

Recently, Attapulgite (ATP), a fibrous nano-clay mineral, was implemented as an additive to improve the sedimentation problem of carbonyl iron based magneto-rheological fluids. The result exhibit similar to SWNT implementation where SEM images clearly showed ATP filled the interspaces among the CI particles explaining the improved dispersion stability which can prevent serious sedimentation problem. This magneto-rheological fluid also exhibits the typical MR performance of an increase in shear stress in an applied magnetic field. [39]

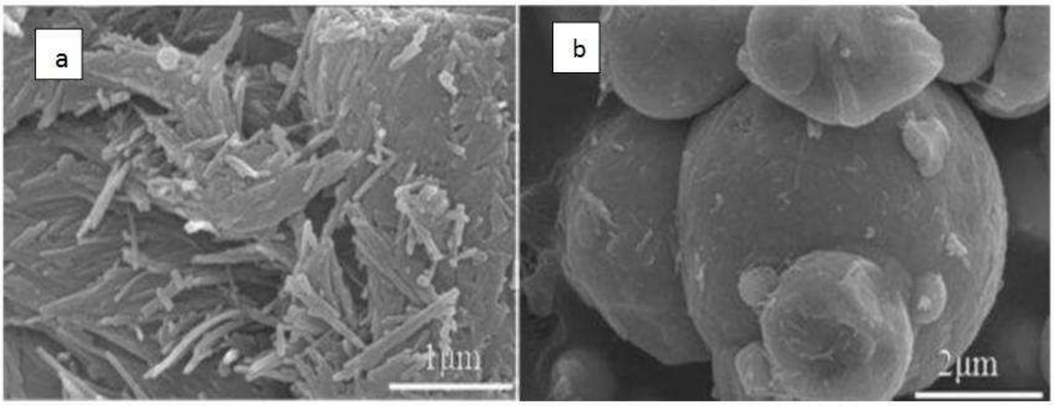

Figure 8 : SEM image of ATP (a) and Carbonyl iron-ATP mixture (b) [39]

Instead of having non-magnetic nano-scale additives (including fumed silica, clays, carbon fibers, and carbon nano-tubes), researchers started to introduce magnetic additives to enhanced the effect of the magneto-rheological fluid. Recently, Jang D et.al added magnetic γ-Fe_2O_3 nano-particle additives to micron-sized CI-based magneto-rheological fluids to improve the yield stress and lessen the sedimentation of the fluid. Rotational rheometer with a parallel-plate measuring cell was used to examine the rheological properties of the fluid in on-state condition. The result was successful where the yield properties improved with added magnetic γ-Fe2O3 nano-particles and the sedimentation of the Magneto-rheological fluid also was reduced. [40]

3. CONCLUSION

The applications of magneto-rheological fluid in various sector showed good technology improvement nowadays. A lot of studies have been made by researchers to utilize this material in daily applications parallel to the technologies development. Besides, the studies on the enhancement of the magneto-rheological fluid application also been done by researchers. Problem of defects and failures also been studied aggressively nowadays. Hard cake, clumping, particles oxidation, Fluid particles separations and stability are the most common failures and defects in magneto-rheological fluid application. Even though some defects and failure cannot be removed or eliminate but it can be managed to specific values.

4. ACKNOWLEDGEMENTS

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