EFFECT OF MILLING TIME ON RHEOLOGICAL PROPERTIES OF PLATE-LIKE CARBONYL IRON PARTICLES IN MAGNETORHEOLOGICAL FLUID

SALIHAH BINTI TAN SHILAN

UNIVERSITI TEKNOLOGI MALAYSIA

EFFECT OF MILLING TIME ON RHEOLOGICAL PROPERTIES OF PLATE-LIKE CARBONYL IRON PARTICLES IN MAGNETORHEOLOGICAL FLUID

SALIHAH BINTI TAN SHILAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia

JULY 2022

DEDICATION

The dedication of this thesis goes to my supervisor, my parents ang all my family members who really supported me during this period. Not forgetting my beloved friends who remained on my side. Thank you very much to all your concerns and kindness.

ACKNOWLEDGEMENT

Praise to Almighty Allah for his uncountable mercy and blessings for giving me good health, determination and patience while completing these research works. First and foremost, I would like to express my deepest gratitude to my supervisor, Prof. Ir. Ts. Dr. Saiful Amri Bin Mazlan for his encouragement, unwavering support, mentorship, and patient from the early stage towards the end of this study. His knowledge, expertise, advice, and inspiration are precious, enabling me to develop good experienced and understanding. Special mention should also go to the Malaysia-Japan International Institute of Technology (MJIIT) for the scholarship supporting me while completing my PhD. Without this financial assistance, the study would not have been possible.

I would like to extend my sincere appreciation to Prof. Dr. Ido, from Nagoya Institute Technology (NIT), Japan, for his guidance and allow me to use their lab and equipment during my 1-year stay in NIT. To my colleagues in Vehicle System Engineering (VSE) and my friends, thank you for all your help, supports and comforting me throughout this journey. Thank you very much to all others who gave a hand, especially technicians from UiTM, UKM and UKM-MTDC, for doing the required testing. May Allah paid your kindness with the best rewards.

Last but not least, I would like to express my gratitude to my family for their never-ending love and trust in my decision. They have always been there and pray for me. Without their support and understanding, none of this would have been possible. I am thankful for everything that they have helped me to achieve.

ABSTRACT

Magnetorheological (MR) fluid is a magnetic field responsive fluid containing polarizable particles and a liquid carrier component. This MR fluid is typically used within the working gap of dampers to provide varied damping forces, depending on magnetic field strength. Generally, maximum yield stress will be increased with the increasing amount of particles in the MR fluid, and consequently enhancing the maximum force output of the device. An additional number of particles also lead to increasing the off-state viscosity and sedimentation of the MR fluid. Researchers have concentrated on improving the properties of particles to overcome the sedimentation problem. Particle shape is a critical factor to enhance the sedimentation stability. Thus, this research aims to synthesize the plate-like carbonyl iron (CI) to enhance the maximum yield stress and stability of the suspension fluids. Several sizes of plate-like CI were produced using the ball milling method, with the variation of milling time. Observation from X-ray Powder Diffraction, Scanning Electron Microscope and Vibrating Sample Magnetometer results showed that milling duration play a crucial role in controlling the plate-like CI's microstructure, morphology, and consequent magnetic properties obtained from the ball-milling route. The crystallography phase of CI particles was conserved after the milling process, and it is flattened, resulting in the enhancement of the particle length and surface area. Accordingly, the plate-like CI obtained a larger contact surface, which builds stronger clusters due to the magnetic field and resulted in higher saturation magnetization than the spherical CI. This study identified that the sedimentation stability of the plate-like CI-based MR fluid increased significantly due to the increase of the friction force resulted from the increase of the surface area of particles. Subsequently, the field-dependent rheological test demonstrated that the yield shear stress of the plate-like CI-based MR fluid increased up to 134% compared to the spherical CI-based MR fluid. In sum, this study found that CI particles which undergo 20 hours of milling has the best parameter to be used in MR fluid.

ABSTRAK

Bendalir Magnetorheological (MR) adalah cecair responsif medan magnet yang mengandungi medan zarah terpolarisasi dan komponen pembawa cecair. Cecair MR ini biasanya digunakan dalam jurang kerja peranti seperti peredam untuk memberikan daya redaman yang bervariasi, bergantung pada kekuatan medan magnet. Secara amnya, tekanan hasil maksimum akan meningkat dengan peningkatan jumlah zarah di dalam cecair MR dan seterusnya meningkatkan output daya maksimum peranti. Walaupun begitu, sejumlah zarah tambahan juga menyebabkan peningkatan kelikatan dan pemendapan cecair MR di luar keadaan. Kebanyakan penyelidik telah menumpukan perhatian untuk meningkatkan sifat zarah dalam mengatasi masalah pemendapan. Bentuk zarah merupakan factor kritikal untuk meningkatkan kestabilan pemendapan. Oleh itu, idea utama penyelidikan ini adalah meleperkan besi karbonil (CI) untuk peningkatan tekanan hasil maksimum dan kestabilan cecair suspensi. Beberapa ukuran CI leper dihasilkan dengan menggunakan kaedah penggilingan bola, dengan variasi tempoh penggilingan. Hasil pemerhatian dari keputusan *X-ray Powder Diffraction, Scanning Electron Microscope* dan *Vibrating* S*ample* Magnetometer menunjukkan bahawa tempoh penggilingan memainkan peranan penting dalam mengawal struktur mikro, morfologi, dan sifat magnetik CI leper yang diperoleh melalui penggilingan bola. Fasa kristalografi zarah CI masih kekal setelah proses penggilingan dan bentuk leper terhasil dengan peningkatan panjang dan luas permukaan zarah. Sehubungan itu, CI leper mempunyai permukaan sentuhan yang lebih besar yang membentuk gugus yang lebih kuat untuk dibentuk kerana medan magnet, dan menghasilkan magnetisasi tepu yang lebih tinggi berbanding dengan CI sfera. Kajian ini mengenalpasti bahawa kestabilan pemendapan cecair MR berasaskan CI leper meningkat dengan ketara disebabkan oleh peningkatan daya geseran yang terhasil daripada pertambahan luas permukaan zarah. Seterusnya, ujian reologi yang bergantung pada medan menunjukkan bahawa tegangan ricih hasil cecair MR berasaskan CI leper meningkat sehingga 134% dibandingkan dengan cecair MR berasaskan CI sfera. Secara konklusinya, kajian ini mendapati zarah CI yang menjalani pengilingan selama 20 jam mempunyai parameter terbaik untuk digunakan dalam cecair MR.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BASF	-	Baden Aniline and Soda Factory
CI	-	Carbonyl iron
CIP	-	Carbonyl iron particles
ER	-	Electro-rheological
MR	-	Magnetorheological
SEM	-	Scanning electron microscopy
VSM	-	Vibrating sample magnetometer
XRD	-	X-ray diffractometer

LIST OF SYMBOLS

A	-	Ampere
a	-	Diameter
B	-	Magnetic flux density
$°C$	-	Degree Celsius
F_{ij}	-	force tensor
H	-	External magnetic field
Hc	-	Coercive Force
kA/m	-	Kilo ampere per meter
kPa	-	Kilo pascal
m	-	Magnetic dipole moment
mT	-	Milli-Tesla
T	-	Tesla
wt %	-	Weight percentage
%	-	Percentage
μ_0	-	Vacuum permeability
μ_f	-	Specific permeability particles
$\mu_s M_s$	-	Saturation magnetization of particles
μ_p	-	Specific permeability carrier fluid
μm	-	Micron meter
η	-	Shear viscosity
η_r	-	Relative viscosity
δ	-	Phase angle
γ	-	Shear strain
$\dot{\gamma}$	-	Shear rates
τ	-	Shear stress
τ_y	-	Yield stress
φ	-	Volume fraction

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Controllable fluids are composed of components that can react to an external excitation field. When exposed to either an electric or a magnetic field, their rheological behaviour goes through exceptional changes. This type of fluid is known as "smart fluid". Some common names for these smart fluids include magnetorheological (MR) fluids, electrorheological (ER) fluids, and ferrofluids. ER fluids are suspensions of extremely small nonconductive but electrically active particles in an insulating fluid. [1] Ferrofluids are a stable colloidal combination of ferrimagnetic and/or ferromagnetic nanoparticles, while MR fluids are suspensions of magnetizable microparticles dispersed in a carrier fluid. MR fluids are garnering more attention than other forms of smart fluids since they are able to produce the maximum stress and can therefore be utilized in a wide variety of applications. This is one of the reasons why MR fluids are becoming increasingly popular.

A magnetic field-responsive fluid is referred to as an MR fluid. This type of fluid is made up of polarizable particles, a non-magnetic liquid carrier, and an additive. Rabinow discovered this controllable fluid in 1947 [2], and it has since been refined by several researchers. MR fluid has a variety of properties that can be used to evaluate performance. These include field-dependent apparent viscosity, yield stress, reaction time to the magnetic field, sedimentation due to particle-to-carrier liquid density mismatch, and chemical stability. In general, as the magnetic field intensity increases, so does the apparent viscosity of the MR fluid. This is because the suspended magnetic particles form chain-like structures in the direction of the applied magnetic field, restricting fluid flow [3]. In other words, the intensity of the applied magnetic field can be used to control rheological properties of MR fluids such as apparent viscosity and yield stress [4]. As a result, when a magnetic field is applied, MR fluid behaves as a non-Newtonian fluid, and the field-dependent yield stress is expressed as a function of the magnetic field [5, 6]. The apparent viscosity of MR fluid is primarily determined by shear rate as well as the magnitude and direction of the applied magnetic field [7]. Furthermore, the response time of MR fluid is the most significant advantage in terms of application, as it is known to be dependent on the strength of the applied magnetic field. Aside from that, temperature has little effect on the operational characteristics of MR fluid, which can be controlled over a wide range of viscosity [5]. Because of its fast response to magnetic field strength, MR fluid requires relatively little power to operate, and up to 100 kPa of dynamic yield stress is represented [8]. When compared to other rheological fluids, this unique property of MR fluid has enabled its use in small devices and a wide dynamic range of application [11-13]. As a result, MR fluid is suitable for a wide range of mechanical applications and is one of the fastest electromechanical interfaces.

In the early stages of development, MR fluids have received less attention than electrorheological (ER) suspensions due to the limitations in applications [7]. Because of this, the enhancement of MR fluid characteristics has been the subject of a lot of research. In general, the maximum yield stress of MR fluid will be enhanced if the particle concentration is increased or if a larger particle size is used [11]. Consequently, an increase in the device's capacity to generate its maximum force can be accomplished. However, the use of larger particle sizes and the rise in particle concentration will raise the off-state viscosity, resulting in poor fluid stability [7, 12, 15, and 16]. Several methods for improving the poor stability of MR fluid have been investigated, including the use of thixotropic additives, electrostatic additives, non-spherical particles, and nanometer-sized particles. The particle shape was discovered to be the critical factor in improving the MR fluid sedimentation stability [7]. Details about the significance of particle shape in MR fluid performance are explained in the next chapter.

1.2 Motivation of Study

The conventional MR fluid has some difficulty finding widespread commercial use due to high manufacturing costs and low yield stress [7]. To increase the output of MR devices, the coils must occupy more space in order to generate a stronger magnetic field, and the increased amount of MR fluid may cause the devices to become heavier. To maintain its low off-state viscosity [13, 14], the number of particles suspended in MR fluid is limited, resulting in a low yield stress. Researchers [11] say that the most important things about MR fluid are a high yield stress, a low viscosity in the off-state, and a low sedimentation rate.

The development of MR fluids with a high yield stress has been intensively studied by researchers in order to improve the application efficiency of MR fluids. The high yield stress of MR fluid was obtained by increasing the volume fraction of particles and employing larger particle sizes [15–17]. Nonetheless, the use of larger particle sizes and a greater volume fraction of particles has increased the MR fluid's off-state viscosity and sedimentation rate [18].

To address the sedimentation issue, researchers have focused on enhancing particle properties. Utilizing thixotropic additives [19,20], electrostatic additives [21], the addition of non-spherical particles [7,22], and nanometer-sized particles [23] have all been used to combat the sedimentation issue of MR fluid. On the other hand, the yield stress has decreased as a direct consequence of the incorporation of these particles. Consequently, this varies according on the composition and the particle size [10].

Later, researchers discovered that particle shape significantly influenced MRF properties [7]. Upadhyay et al. [15] reported that flaky-shaped pure iron decreased sedimentation without impairing magnetic properties. Ido et al. [24] investigated the impact of particle shape on damping force. It demonstrates that nickel-iron with an irregular shape achieves a greater damping force than nickel-iron with a spherical shape. Bell et al. [12] reported the effect of suspensions containing magnetic wires on the enhancement of yield stress. However, the most cost effective particle to be use is carbonyl iron. In sum, plate-like shape particles promoted the increasing of magnetisation, enhancing the effective permittivity more than that of the spheres or needles shape particles due to the polarization resulting from the large plate diameter.

Quite a few of researchers have addressed the impact of plate-like CI on MR fluid properties. Though, no researchers have thoroughly investigated the relation of aspect ratio of plate-like CI towards MR performance. Most of the researcher, only be used one type or size of the plate-like particles produced by a company and did not discuss the manufacturing (milling) procedure. Therefore, it is necessary to investigate the essential properties of plate-like CI, such as particle size and magnetic saturation.

1.3 Research Objectives

This research aims to investigate the effect of milling time towards the MR fluid base plate-like CI performance. The specific objectives of this study are as follows:

(a) To investigate the characteristics of plate-like CI with different milling time.

(b) To analyse the sedimentation rate of plate-like CI produced with different milling time.

(c) To evaluate the effects of plate-like CI size on the field-dependent rheological properties of MR fluid.

1.4 Research Scope

The scope of the research is specified on the experimental investigation of the new produced plate-like CI-based MR fluid and comprehensive characterization to confirm the enhancement of yield stress without increasing the sedimentation rate for better applications performance. This includes:

(a) The plate-like shape of CI particles is fabricated by using the ball milling process. Several sizes of the plate-like CI will be produced to identify the significance of particles aspect ratio on MR fluid properties.

(b) The characterization of plate-like CI such as particle size and shape morphology, crystallography, and magnetic properties (on-state) are investigated.

(c) The sedimentation rate of plate-like CI-based MR fluid is identified by placing the MR fluid in a vertical cylindrical container at room temperature.

(d) The rheological characterisation is analysed in the rotational and oscillatory mode under off and on-state conditions at room temperature. This testing is performed to understand the correlation between CI particle shapes towards yield stress in MR fluid.

1.5 Thesis Outline

This thesis is organised into five segments. For the benefit of readers who are not previously familiar with the topic, this thesis included an introductory chapter that provides a concise overview of MR fluids as well as their behaviour when subjected to the presence of magnetic fields. Additionally, this chapter described the findings of prior research and how they led to the aims of this study. At the end of each chapter in this thesis is a summary that outlines the accomplishments and results that were established in that particular chapter. The remaining portions of this thesis are structured in the following manner:

Chapter 2 presents the theoretical basis and a literature review concerning previous works on MR fluid materials. This includes recent developments in magnetic materials, compositions, particle shape, the rheology of suspensions, and the stability of MR fluid.

Chapter 3 discusses the experimental approaches that were utilised to construct the plate-like CI with different milling time, combined with an examination of the characteristics of the particles created.

Chapter 4 provides a comparative analysis of plate-like CI generated with varied milling times. The behaviour of various CI particle types is investigated and extensively described. In addition, the effect of different milling times on the sedimentation rate and rheological characteristics of MR fluid are investigated in detail.

Chapter 5 summarises and concludes the overall findings from the experimental analysis. The contribution study that corresponds to the objectives is outlined. For the continuation of the study, further research recommendations are given.

REFERENCES

[1] D. Susan-resiga, and L. Vekas, "From High Magnetization Ferrofluids To Nano-Micro Composite Magnetorheological Fluids: Properties And Applications", *Romanian Reports in Physics*, 70, 501, 2018.

[2] A. G. Olabi and A. Grunwald, "Design And Application Of Magneto-Rheological Fluid," *Mater. Des.*, vol. 28, no. 10, pp. 2658–2664, 2007.

[3] F. D. Goncalves, M. Ahmadian, and J. D. Carlson, "Investigating The Magnetorheological Effect At High Flow Velocities," *Smart Mater. Struct.*, vol. 15, no. 1, pp. 75–85, 2006.

[4] F. D. Goncalves, "A Review Of The State Of The Art In Magnetorheological Fluid Technologies - Part I: Mr Fluid And Mr Fluid Models," *Shock Vib. Dig.*, vol. 38, no. 3, pp. 203–219, 2006.

[5] R. Turczyn, M. Kciuk, and F. Materials, "Technologies, Preparation And Study of Model Magnetorheological Fluids," vol. 27, no. 2, pp. 131–134, 2008.

[6] D. Baranwal and T. S. Deshmukh, "MR-fluid Technology and Its Application-A Review," vol. 2, no. 12, pp. 563–569, 2012.

[7] R. C. Bell, E. D. Miller, J. O. Karli, A. N. Vavreck, and D. T. Zimmerman, "Influence of Particle Shape on The Properties of Magnetorheological Fluids," *International Journal of Modern Physics B*, vol. 21, pp. 5018–5025, 2007.

[8] Z. Jian, Z. Jin-Qiu, and j. I. A. Jin-Feng, "Characteristic Analysis Of Magnetorheological Fluid Based On Different Carriers," vol. 15, pp. 252–255, 2008.

[9] K. Shah, D. X. Phu, M. S. Seong, R. V Upadhyay, and S.B. Choi, "A Low Sedimentation Magnetorheological Fluid Based On Plate-Like Iron Particles, And Verification Using A Damper Test," *Smart Mater. Struct.*, vol. 23, no. 2, p. 027001, 2014.

[10] J. Wang, G. Meng, N. Feng, and E. J. Hahn, "Dynamic Performance And Control Of Squeeze Mode Mr Fluid Damper–Rotor System," *Smart Mater. Struct.*, vol. 14, no. 4, pp. 529–539, 2005.

[11] R. Thomas and F. Rochester, *United States Patent,* 1997.

[12] R. F. Ierardi and A. J. F. Bombard, "Off-State Viscosity And Yield Stress Optimization Of Magneto-Rheological Fluids: A Mixture Design Of Experiments Approach," *J. Phys. Conf. Ser.*, vol. 149, p. 012037, 2009.

[13] J. E. Kim, J. D. Ko, Y. D. Liu, I. G. Kim, and H. J. Choi, "Effect Of Medium Oil On Magnetorheology Of Soft Carbonyl Iron Particles," *Ieee Trans. Magn.*, vol. 48, no. 11, pp. 3442–3445, 2012.

[14] M. Ashtiani, S.H. Hashemabadi, and A. Ghaffari. "A review on the magnetorheological fluid preparation and stabilization." *Journal of magnetism and Magnetic Materials* 374, 716-730, 2015.

[15] J. H. Park, b. D. Chin, and o. O. Park, "Rheological Properties And Stabilization Of Magnetorheological Fluids In A Water-In-Oil Emulsion.," *J. Colloid Interface Sci.*, vol. 240, no. 1, pp. 349–354, 2001.

[16] Y. Tian, Y. Meng, and S. Wen, "Particulate Volume Effect In Suspensions With Strong Electrorheological Response," *Mater. Lett.*, vol. 57, no. 19, pp. 2807–2811, 2003.

[17] B. D. Chin, J. H. Park, M. H. Kwon, and O. O. Park, "Rheological Properties And Dispersion Stability Of Magnetorheological (MR) Suspensions," *Rheol. Acta*, vol. 40, no. 3, pp. 211–219, 2001.

[18] I. Ismail, "Stress Resistance And Fluid Particle Separation of Magnetorheological Fluid In Squeeze Mode,"*Thesis of Dublin City University,* 2012.

[19] J. D. Carlson, "What Makes A Good MR Fluid?," *J. Intell. Mater. Syst. Struct.*, vol. 13, no. 7–8, pp. 431–435, jul. 2002.

[20] J. D. Carlson and M. R. Jolly, “MR Fluid, Foam and Elastomer Devices,” vol. 10, pp. 555–569, 2000.

[21] A. A. Zaman and C. S. Dutcher, “Viscosity Of Electrostatically Stabilized Dispersions Of Monodispersed, Bimodal, And Trimodal Silica Particles,” *J. Am. Ceram. Soc.*, vol. 89, no. 2, pp. 422–430, feb. 2006.

[22] R. V Upadhyay, Z. Laherisheth, and K. Shah, “Rheological Properties Of Soft Magnetic Flake Shaped Iron Particle Based Magnetorheological Fluid In Dynamic Mode,” *Smart Mater. Struct.*, vol. 23, p. 015002, 2014.

[23] J. H. Park, M. H. Kwon, and O. O. Park, “Rheological Properties And Stability Of Magnetorheological Fluids Using Viscoelastic Medium And Nanoadditives,” vol. 18, no. 5, pp. 580–585, 2001.

[24] Y. Ido, T. Yamaguchi, and Y. Kiuchi, “Distribution Of Micrometer-Size Particles In Magnetic Fluids In The Presence Of Steady Uniform Magnetic Field,” *J. Magn. Magn. Mater.*, vol. 323, no. 10, pp. 1283–1287, may 2011.

[25] J. H. Park and o. O. Park, “Electrorheology And Magnetorheology,” vol. 13, no. 1, pp. 13–17, 2001.

[26] J. Wang and G. Meng, “Magnetorheological Uid Devices : Principles , Characteristics And Applications In Mechanical Engineering,” vol. 215, pp. 165–174, 1948.

[27] I. B. Jang, H. B. Kim, J. Y. Lee, J. L. You, H. J. Choi, and M. S. Jhon, “Role Of Organic Coating On Carbonyl Iron Suspended Particles In Magnetorheological Fluids,” *J. Appl. Phys.*, vol. 97, no. 10, p. 10q912, 2005.

[28] Y. D. Liu and H. J. Choi, "Electrorheological Fluids: Smart Soft Matter And Characteristics",*Soft Matter, 8, 2012.*

[29] S. Bahl, H. Nagar, I. Singh, S. Sehgal, "Smart Materials Types, Properties and Applications: A review", *Materials Today: Proceedings,* 28, 2020.

[30] G. Song and M. Zeng, "A Thin-Film Magnetorheological Fluid Damper/Lock," *Smart Mater. Struct.*, vol. 14, no. 2, pp. 369–375, 2005.

[31] P. Wong, W. Bullough, C. Feng, and S. Lingard, "Tribological Performance Of A Magneto-Rheological Suspension," *Wear*, vol. 247, no. 1, pp. 33–40, 2001.

[32] A. G. Olabi and a grunwald, "Design And Application Of Magneto-Rheological Fluid," *Mater. Des.*, vol. 28, no. 10, pp. 2658–2664, 2007.

[33] D. J. Klingenberg, "Magnetorheology : Applications And Challenges," vol. 47, no. 2, pp. 246–249, 2001.

[34] R. B. Yang and w.-f. Liang, "Microwave Properties Of High-Aspect-Ratio Carbonyl Iron/Epoxy Absorbers," *J. Appl. Phys.*, vol. 109, no. 7, p. 07a311, 2011.

[35] K. D. Weiss, J. D. Carlson, and D. A nixon, "Viscoelastic Properties Of Magnetorheological And Electrorheological Fluids," *j. Intell. Mater. Syst. Struct.*, vol. 5, no. 6, pp. 772–775, 1994.

[36] S. Genc, and P. Phule "Rheological Properties Of Magnetorheological Fluids," vol. 11, pp. 140–146, 2002.

[37] C. Guerrero-sanchez, T. Lara-ceniceros, E. Jimenez-regalado, M. Raşa, and U. S. Schubert, "Magnetorheological Fluids Based On Ionic Liquids," *Adv. Mater.*, vol. 19, no. 13, pp. 1740–1747, 2007.

[38] S.l Genç , "Synthesis And Properties Of Magnetorheological (MR) Fluids," *Thesis of University of Pittsburgh,* 2002.

[39] A. Chaudhuri, "Rheological Parameter Estimation For A Ferrous Nanoparticle-Based Magnetorheological Fluid Using Genetic Algorithms," *J. Intell. Mater. Syst. Struct.*, vol. 17, no. 3, pp. 261–269, 2006.

[40] M. Kciuk, R. Turczyn, F. Materials, and P. Technologies, "Properties And Application Of Magnetorheological Fluids," vol. 18, no. 1, pp. 127–130, 2006.

[41] G. Bossis, P. Khuzir, S. Lacis, and O. Volkova, “Yield Behaviour Of Magnetorheological Suspensions,” *J. Magn. Magn. Mater.*, vol. 258–259, pp. 456–458, 2003.

[42] G. Bossis, S. Lacis, A. meunier, and O. Volkova, “Magnetorheological Fluids,” *J. Magn. Magn. Mater.*, vol. 252, no. 50, pp. 224–228, 2002.

[43] S. P. Rwei, H. Y. Lee, S. D. Yoo, l. Y. Wang, and J. G. Lin, “Magnetorheological Characteristics of Aqueous Suspensions That Contain Fe_3O_4 Nanoparticles,” *Colloid Polym. Sci.*, vol. 283, no. 11, pp. 1253–1258, 2005.

[44] K. D.weiss, J. D. Carlson, D. A. Nixon, "Method And Magnetorheological Fluid Formulations For Increasing The Output Of A Magnetorheological Fluid," *United States Patent,* 6,027,664, 2000.

[45] G. Dodbiba, H. S. Park, K. Okaya, and T. Fujita, “Investigating Magnetorheological Properties Of A Mixture Of Two Types Of Carbonyl Iron Powders Suspended In An Ionic Liquid,” *J. Magn. Magn. Mater.*, vol. 320, no. 7, pp. 1322–1327, 2008.

[46] O. Ashour, C. A. Rogers, W. Kordonsky, "Magnetorheological Fluids: Materials, Characterization, and Devices" *Journal of Intelligent Material Systems and Structures,* vol. 7, issue 2, 1996.

[47] Cl. Kormann, H.M. Laun and H.J. Richter, "Mr Fluids with Nano-Sized Magnetic Particles" *International Journal of Modern Physics B,* vol. 10, no. 23n24, pp. 3167-3172, 1996.

[48] M. J. Wilson, A. Fuchs, and F. Gordaninejad, "Development And Characterization Of Magnetorheological Polymer Gels" *Journal of Applied Polymer Science,* vol. 84, issue 14, pp. 2733-2742, 2002.

[49] M. R. Jolly, Jonathan W. Bender, J. David Carlson, "Properties and Applications of Commercial Magnetorheological Fluids" *Journal of Intelligent Material Systems and Structures,* vol. 10, issue 1, 1999.

[50] V. R. Iyengar and R. T. Foister, "Optimized Synthetic Base Liquid for Magnetorheological Fluid Formulations", *US Patent* No. 6,638,443 B2, 2003.

[51] D. Y. Lee, Y. T. Choi, N. M. Wereley. "Performance Analysis of ER/MR Impact Damper Systems using Herschel-Bulkley Model". *Journal of Intelligent Material Systems and Structures,* 13(7-8), 525-531, 2002.

[52] F. D. Goncalves, "Characterizing the Behaviour of Magnetorheological Fluids at High Velocities and High Shear Rates" *Virginia Tech*, 2005.

[53] E. C. McIntyre, F.E. Filisko, "Squeeze Flow of Electrorheological Fluids Under Constant Volume", *Journal of Intelligent Material Systems and Structures*, 18(12), 1217-1220, 2007.

[54] P. Sheng, W. Wen, "Electrorheological Fluids: Mechanisms, Dynamics, and Microfluidics Applications", *Annual Review of Fluid Mechanics*, 44(1), 143-174, 2012.

[55] A. Dang, L. Ooi, J. Fales, and P. Stroeve, "Yield Stress Measurements of Magnetorheological Fluids in Tubes", *Ind. Eng. Chem. Res.* 39, 7, 2269–2274, 2000.

[56] R.T. Foister, V.R. Iyengar, S.M. Yurgelevic, "Low Cost MR Fluids With Powdered Iron", *U.S. Patent,* 6, 787,058 B2, 2004.

[57] S. A. Mazlan, "The Behaviour of Magnetorheological Fluids In Squeeze Mode" *Thesis of Dublin City University,* 2008.

[58] Y. Qi, L. Zhang and W. Wen, "Anisotropy Properties of Magnetic Colloidal Materials", *Journal of Physics D: Applied Physics*, vol. 36, 110-114, 2003.

[59] K. Butter, P. H. Bomans, P. M. Frederik, G. J. Vroege, and A. P. Philipse, "Direct Observation of Dipolar Chains in Ferrofluids in Zero Field Using Cryogenic Electron Microscopy", *Journal of Physics Condensed Matter,* vol. 15, no. 15, s1451-s1470, 2003.

[60] G. L. Gulley and R. Tao, "Structures of an Electrorheological Fluid", *Physical Review E*, vol. 56, no. 4, 4328-4336, 1997.

[61] T. Shiraishi, S. Morishita and H. P. Gavin, "Estimation of Equivalent Permeability in Magnetorheological Fluid Considering Cluster Formation of Particles", *Journal of Applied Mechanics*, Transactions of the ASME, vol. 71, no. 2, 201-207, 2004.

[62] B. -J. de Gans, H. Hoekstra and J. Mellema, "Non-Linear Magnetorheological Behaviour of an Inverse Ferrofluid", *Faraday Discussions*, vol. 112, 209- 224, 1999.

[63] T. E. Faber, "Fluid Dynamics for Physicists", *Cambridge University Press*, 1995.

[64] N. de Nevers, "Fluid Mechanics for Chemical Engineers 2nd Ed", *McGraw-Hill Inc.*, New York, 1991.

[65] I. H. Shames, "Mechanics of Fluids, 3rd Ed"., *McGraw-Hill Inc.*, New York, 1992.

[66] S. J. Dyke, B. F. Spencer Jr., M. K. Sain and J. D. Carlson, "An Experimental Study of MR Dampers for Seismic Protection", *Smart Materials and Structures*, vol. 7, 693-703, 1998.

[67] Y Tian, S Wen, Y Meng, "Compressions of Electrorheological Fluids Under Different Initial Gap Distances". *Physical Review E.*, 67(5), 051501, 2003.

[68] C.A. Shook, and A.S. Bartosik, "Particle—Wall Stresses In Vertical Slurry Flows", *Powder Technology,* vol. 81, 2, 117-124,1994.

[69] K Toda, H Furuse, "Extension of Einstein's Viscosity Equation To That For Concentrated Dispersions of Solutes and Particles", *Journal of bioscience and bioengineering,* vol. 102, 6, 524-528, 2006.

[70] QH Nguyen, S.B. Choi, "Optimal Design Methodology of Magnetorheological Fluid Based Mechanisms", *Smart Actuation and Sensing Systems: Recent Advances and Future Challenges,* Chapter 14, 347-382, 2012.

[71] J. E. Coolidge; R. W. Halberg, "Some Properties of Magnetic Fluids", *Transactions of the American Institute of Electrical Engineers, Part I: Communication and Electronics,* vol. 74, issue: 2, 1955.

[72] JM Ginder, LC Davis, "Rheology of Magnetorheological Fluids: Models And Measurements", *International Journal of Modern Physics B,* vol. 10, pp. 3293-3303, 1996.

[73] RT Foister, "Magnetorheological fluids", *US Patent* 5,667,715, 1997.

[74] HA Barnes, JF Hutton, K Walters, "An Introduction to Rheology", *Rheology Series 3,* 1989.

[75] G Dodbiba, HS Park, K Okaya, T Fujita, "Investigating Magnetorheological Properties Of A Mixture Of Two Types Of Carbonyl Iron Powders Suspended In An Ionic Liquid", *Journal of Magnetism and Magnetic Materials,* Vol. 320, 7, April, 1322-1327, 2008.

[76] B. Zhang, Y. Feng, J. Xiong, Y. Yang, L. Huaixian, "Microwave-Absorbing Properties of De-Aggregated Flake-Shaped Carbonyl-Iron Particle Composites at 2–18 GHz" *IEEE Trans. Magn.*, 42, pp. 1778-1781, 2006.

[77] P. P. Phulé, "Magnetorheological Fluid", *US Patent,* 5985168, 1999.

[78] C. Fang, B. Y. Zhao, L. S. Chen, Q. Wu, N. Liu and K. A. Hu, "The Effect of the Green Additive Guar Gum on the Properties of Magnetorheological Fluid", *Smart Materials and Structures*, vol. 14, no. 1, n1-n5, 2005.

[79] A. A. Zaman and C. S. Dutcher, "Viscosity of Electrostatically Stabilized Dispersions of Monodispersed, Bimodal, and Trimodal Silica Particles", *Journal of the American Ceramic Society*, vol. 89, no. 2, 422-430, 2006.

[80] AK. El-Wahed. "The Influence of Solid-Phase Concentration on the Performance of Electrorheological Fluids in Dynamic Squeeze Flow". *Materials and Design.*, 32(3), 1420- 1426, 2011.

[81] L Vékás, D Bica, I Potencz, D Gheorghe, O Bălău, M Raça. "Concentration and Composition Dependence of Rheological and Magnetorheological Properties of some Magnetic Fluids". *Progress in Colloid and Polymer Science*, 117, 104-109, 2002.

[82] J.Vicente, F Vereda, JP Segovia-Gutierrez, MP Morales, R Hidalgo-Alvarez. "Effect of Particle Shape in Magnetorheology". *Journal of Rheology.*, 54(6), 1337-1362, 2010.

[83] X Duan, W Luo, H Chen, Y He. "The Effect of Particle Shape on Water-Free Mica ER Fluids". *Journal of Intelligent Material Systems and Structures.*, 11(1), 43-46, 2000.

[84] AM Trendler, H Bose. "Influence of Particle Size on the Rheological Properties of Magnetorheological Suspensions". *International Journal of Modern Physics B: Condensed Matter Physics; Statistical Physics; Applied Physics.*, 19(7-9), 1416-1422, 2005.

[85] E Lemaire, A Meunier, G Bossis, J Liu, D Felt, P Bashtovoi, "Influence of the Particle Size on the Rheology of Magnetorheological Fluids". *Journal of Rheology.*, 39(5), 1011-1020, 1995.

[86] P. Carletto, and G. Bossis, "Field-Induced Structures and Rheology of a Magnetorheological Suspension Confined Between Two Walls", *Journal of Physics Condensed Matter*, vol. 15, no. 15, S1437-S1449. 161, 2003.

[87] T. Ukai and T. Maekawa, "Patterns Formed by Paramagnetic Particles in a Horizontal Layer of a Magnetorheological Fluid Subjected to a DC Magnetic Field", *Physical Review E, Statistical, Nonlinear, and Soft Matter Physics*, vol. 69, no. 3, part 1, 032501, 2004.

[88] T. M. Simon, F. Reitich, M. R. Jolly, K. Ito and H. T. Banks, "The Effective Magnetic Properties of Magnetorheological Fluids", *Mathematical and Computer Modelling*, vol. 33, no. 1-3, 273-284, 2001.

[89] R. H. Davis, Y. Zhao, K. P. Galvin and H. J. Wilson, "Solid-Solid Contacts Due to Surface Roughness and Their Effects on Suspension Behaviour", *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences,* vol. 361, no. 1806, 871-894, 2003.

[90] J. A. Starkovich and E. M. Shtarkman, "High Yield Stress Magnetorheological Material for Specacraft Applications", *US Patent* 6610404, 2003.

[91] B. D. Chin, J. H. Park, M. H. Kwon, and O. O. Park. "Rheological Properties and Dispersion Stability of Magnetorheological (MR) Suspensions". *Rheologica Acta.*, 40(3), 211-219, 2001.

[92] A. Trendler, and H. Bose. "Experimental Studies on Magnetorheological Model Suspensions". *International Journal of Modern Physics B: Condensed Matter Physics; Statistical Physics; Applied Physics.*, 21(28), 4967-4973, 2007.

[93] J. M. Ginder, L. C. Davis, and L. D. Elie. "Rheology of Magnetorheological Fluids: Models and Measurements". *International Journal of Modern Physics B.*, 10(23), 3293-3303, 1996.

[94] J. H. Park, B. D. Chin, O. O. Park. "Rheological Properties and Stabilization of Magnetorheological Fluids in a Water-in-Oil Emulsion". *Journal of Colloid and Interface Science.*, 240, 349-354, 2001.

[95] J. M. Ginder, M. E. Nichols, L. D. Elie and J. L. Tardiff. "Magnetorheological Elastomers: Properties and Applications. in: Wuttig MR", *Smart Structures and Materials,* Smart Materials Technologies; Newport Beach, CA, USA: SPIE, P. 131-138, 1999.

[96] M. Z. Sengun, R. F. Probstein. "Bimodal Model of Slurry Viscosity with Application to Coal-Slurries. Part 1. Theory and Experiment". *Rheologica Acta.*, 28(5), 382-393,1989.

[97] N. M. Wereley, A. Chaudhuri, J. Yoo, S. John, S. Kotha, and A. Suggs, "Bidisperse Magnetorheological Fluids using Fe Particles at Nanometer and Micron Scale". *Journal of Intelligent Material Systems and Structures.*, 17(5, 393-401, 2006.

[98] L. Vekas. "Ferrofluids and Magnetorheological Fluids", *Advances in Science and Technology.*, 54, 127-136, 2008.

[99] J. Ulicny, M. Balogh, N. Potter, and R. Waldo, "Magnetorheological Fluid Durability Test-Iron Analysis", *Materials Science and Engineering: A.*, 443(1-2), 16-24, 2007.

[100] M. T. Lopez-Lopez, P. Kuzhir, A. Meunier, and G. Bossis. "Synthesis and Magnetorheology of Suspensions of Cobalt Particles with Tunable Particle Size". *Journal of Physics: Conference Series.*, 149, 012073, 2009.

[101] R. C. Bell, J. O. Karli, A. N. Vavreck, D. T. Zimmerman, G. T. Ngatu, and N. M. Wereley. "Magnetorheology of Submicron Diameter Iron Microwires Dispersed in Silicone Oil". *Smart Materials and Structures.*, 17(1), 015028, 2008.

[102] H. Chiriac, G. Stoian, and M. Lostun. "Magnetorheological Fluids Based on Amorphous Magnetic Microparticles". *Journal of Physics: Conference Series.*, 149, 2009.

[103] H. Chiriac, and G. Stoian. "Influence of Particle Size Distributions on Magnetorheological Fluid Performances". *Journal of Physics: Conference Series.*, 200(7), 072095, 2010.

[104] S. R. Gorodkin, W. I. Kordonski, E. V. Medvedeva, Z. A. Novikova, A.B. Shorey, S. D. Jacobs, "A Method and Device for Measurement of a

Sedimentation Constant of Magnetorheological Fluids". *Review of Scientific Instruments*., 71(6), 2476, 2000.

[105] M. Kciuk, and R. Turczyn. "Properties and Application of Magnetorheological Fluids". *Journal of Achievements in Materials and Manufacturing Engineering*., 18(1-2), 127-130, 2006.

[106] J. D. Carlson, D. M. Catanzarite, K. A. S. Clair. "Commercial Magneto-Rheological Fluid Devices". *International Journal of Modern Physics B*., 10(23-24), 2857-2856, 1996.

[107] E. C. McIntyre, and F. E. Filisko. "Squeeze Flow of Electrorheological Fluids Under Constant Volume". *Journal of Intelligent Material Systems and Structures*., 18(12), 1217-1220, 2007.

[108] P. Sheng, and W. Wen. "Electrorheological Fluids: Mechanisms, Dynamics, and Microfluidics Applications". *Annual Review of Fluid Mechanics*., 44(1), 143-174, 2012.

[109] I. Ivanova, and V. Mechtcherine ", Effects of Volume Fraction and Surface Area of Aggregates on the Static Yield Stress and Structural Build-Up of Fresh Concrete", *Materials, 13*(7), 1551, 2020.

[110] J. Vicente, F. Vereda, J. P. S. Gutierrez, M. P. Morales, and R. H. Alvarez, "Effect of particle shape in magnetorheology", *Journal of Rheology,* 54, 1337, 2010.

[111] H. See, "Field Dependence of the Response of a Magnetorheological Suspension Under Steady Shear Flow and Squeezing Flow", *Rheologica Acta*, 42(1), 86-92, 2003

Appendix A

LIST OF PUBLICATIONS

Journal

1. Nurul Azhani Yunus, Saiful Amri Mazlan, Ubaidillah, Siti Aishah Abdul Aziz, **Salihah Tan Shilan** and Nurul Ain Abdul Wahab, Thermal Stability and Rheological Properties of Epoxidized Natural Rubber-Based Magnetorheological Elastomer, *Int. J. Mol. Sci.* 2019, *20*(3), 746. **(Q1, IF:4.556)**

2. Muntaz Hana Ahmad Khairi, Saiful Amri Mazlan, Siti Aishah Abdul Aziz, Ubaidillah and **Salihah Tan Shilan**, Performance of Magnetorheological Elastomer Based Green Epoxidized Natural Rubber/Sucrose Acetate Isobutyrate Hybrid Matrix, *IOP Conf. Series: Materials Science and Engineering*, 342, 012034, 2018.

3. Abdollah Hajalilou, Saiful Amri Mazlan, **Salihah Tan Shilan**, Ebrahim Abouzari-Lotf, Enhanced magnetorheology of soft magnetic carbonyl iron suspension with binary mixture of Ni-Zn ferrite and Fe3O4 nanoparticle additive, *J. Colloid and Polymer Science*, Issue 9(2017). **(Q3, IF:1.447)**

4. **Salihah Tan Shilan**, Saiful Amri Mazlan, Yasushi Ido, Abdollah Hajalilou, Balachandran Jeyadevan, Seung-Bok Choi and Nurul Azhani Yunus, A Comparison of Field-Dependent Rheological Properties Between Spherical and Plate-Like Carbonyl Iron Particles-Based Magnetorheological Fluids, *Smart Material Structure*, Vol. 25, (2016) 095025. **(Q1, IF:2.909)**

5. **S. T. Shilan,** S. A. Mazlan, M. H. A. Khairi and Ubaidillah, Properties of Plate-Like Carbonyl Iron Particle for Magnetorheological Fluid, *Journal of Physics: Conference Series*, 776 (2016) 012033. **(IF:0.5)**

6. N.A.Yunus, S.A.Mazlan, Ubaidillah, S.A.A.Aziz, M.H.Ahmad Khairi, N.A.A.Wahab and **S.T.Shilan,** Investigation on Magnetic Field Dependent Modulus of Epoxidized Natural Rubber Based Magnetorheological Elastomer, *Journal of Physics: Conference Series*, 776 (2016) 012024. **(IF:0.5)**