Investigation on the Effect of the Ferrous Particles Size on the Impact Absorption Capability of Magnetorheological Elastomer

Khisbullah Hudha
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
57000 Kuala Lumpur, Malaysia
k.hudha@upnm.edu.my

Normidatul Salwa Sobri
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
57000 Kuala Lumpur, Malaysia
salwasobri96@gmail.com

Kavin Sumasundram
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
57000 Kuala Lumpur, Malaysia
kavin.suma@gmail.com

Nur Akmal Haniffah
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
57000 Kuala Lumpur, Malaysia
nurakmal@upnm.edu.my

Zulkiffli Abd Kadir
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
57000 Kuala Lumpur, Malaysia
zulkiffli@upnm.edu.my

Mohd Sabirin Rahmat
Faculty of Engineering and Built Environment
MAHSA University
42610, Jenjarom, Selangor
sabirin.rahmat@gmail.com

***Abstract*—This study presents the effect of ferrous particles size on impact absorption capability using magnetorheological elastomer (MRE). This study aims to determine the optimum parameter of ferrous particle size for MRE to obtain the maximum impact absorption capability performance. In order to develop MRE, the composition of MRE RTV silicon rubber, hardener, and CI particles with size of 20, 40, and 60 µm are investigated. In real-life applications, the optimum performance of MRE is influenced by the size of ferrous particles. Therefore, the preparation of MRE material is evaluated through experimentation to obtain optimum MRE composition parameters. In this study, three models of isotropic MRE were tested in off-state and on-state conditions with input current values of 0A, 0.5A, 1A, 1.5A, and 2A. The impact test machine was used to validate its performance in impact absorption capability. Validation of the performance is done by evaluating the response of the damping force of MRE material. As a result, this study proves that the size of Carbonyl Iron particles and the value of injected current can affect the response of damping force of MRE. Since the impact absorption capability of MRE can be determined by the response of damping force, the optimum size of CI particle to absorb the maximum impact is determined in this experiment. Therefore, the objective of this study is justified by finding the optimum CI particle size for best impact absorption capability, which is 60 µm in on-state condition with 2A input current.**

***Keywords*—magnetorheological elastomer, ferrous particle size, impact absorption**

I. Introduction

This Magnetorheological Fluid (MRF), MR foams and magnetorheological elastomers are considered magnetorheological (MR) materials. Magnetorheological elastomer is the stable version of magnetorheological fluids that includes various composite materials. Magnetorheological elastomer holds a place in engineering-based implications for vibration isolation systems and vibration control in damping [1].

Magnetorheological elastomer (MRE) damper is a smart material with varying mechanical properties when the magnetic field is applied. An electromagnetic field manipulates the material's resistance, overall stiffness, and damping properties [2]. This study investigates the impact absorption capability of the isotropic MRE in the presence of the external magnetic field. MRE contains ferrous particles, liquid rubber, binder, and additives. The size of magnetic particles in the composition is one of the critical factors that affect the impact absorption capability of MRE.

The elastomer matrix, the particle content, and the external magnetic field are applied to determine the dynamic properties of isotropic MREs. To obtain the essential model of isotropic MRE, the MRE must be modelled theoretically and create the design of the experiment so that the dynamic response of isotropic MRE can be predicted [3]. For isotropic MRE, it was made sure that the particles were uniformly distributed in the whole volume. No magnetic field is applied in the curing process of isotropic MRE [4]. When magnetic fields are applied to MRE, the metallic particles tend to line up themselves according to the conduct of the applied magnetic field. This realignment of the micron-sized particles raises the specimen's stiffness based on the strength of the magnetic field. The schematics of this phenomenon are depicted in Figure 1.

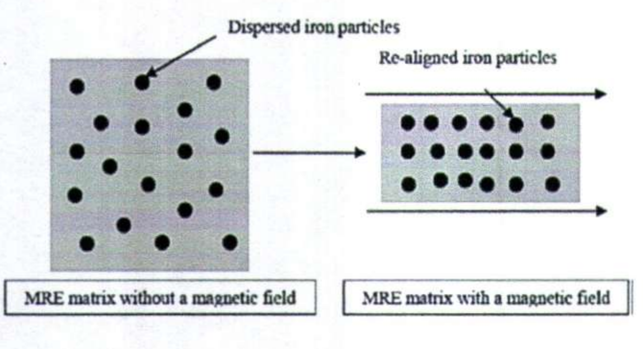

Fig. 1. Alignment of particles [5]

MRE can contain various sizes of ferromagnetic particles in their composition. The optimum size of the ferromagnetic particle to achieve the maximum impact absorption capability in MRE for cyclic loading is determined in many studies. However, the studies that validate the maximum impact absorption capability under the influence of CI particle size

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

for impact loading are still limited. Therefore, the size of ferromagnetic particles needs to be determined for optimum composition in MRE and validate its best performance in impact absorption capability in real-life applications.

MRE have gained considerable observation for their immense perspective in engineering applications over the last few decades [6]. MR elastomers reveal a particular field-contingent material characteristic and resolve significant problems faced by MRFs, such as CI particle deposition, environmental pollution, and sealing issues. The research and development of MR elastomer products, including vibration absorbers, vibration isolators, base isolators, and sensor devices, has been presented in a detailed analysis [7].

II. FABRICATION OF MRE

Fabrication of MRE involved the curing process of polymers [8]. The room temperature will harden the silicon rubber produced by Craftivity Malaysia as a fabrication matrix. The weight ratio for the silicon rubber to Carbonyl Iron particles was set to be 3:7. The total weight of each MRE material fabricated is 30g, with a composition of 21g of Carbonyl Iron particle and 9g of RTV Silicon rubber. Carbonyl Iron particles with 20μm, 40μm, and 60μm diameters (Sigma-Aldrich USA) produce variable stiffness when applying different magnetic fields. Table I shows the composition of materials in MRE.

TABLE I. COMPOSITION IN MRE MATERIALS

Material	Percentage of Composition
RTV Silicon Rubber	70% (21g)
Carbonyl Iron Particle	30% (9g)
Hardener	3% from the amount of CI particles (0.27g)

The Carbonyl Iron particles were mixed with silicone rubber. Then it was stirred until it turned into greyish colour. The greyish colour proves that the Carbonyl Iron particle and RTV Silicon rubber is well mixed. Then, a hardener was added to the mixture of CI particle and RTV silicon rubber. The hardener added was 3% to the amount of RTV silicon rubber. All the mixtures were stirred until they turned into semi-solid. The semi-solid mixture was then transferred to the mould for the curing process. Silicon spray is sprayed into the mould so that the mixture does not stick to the mould walls. The curing process took place for 24 hours, as shown in Figure 2. Figure 3 presents the materials used for the fabrication process of MRE. The mixture was placed in the mould evenly to avoid the porosity and air bubbles in the MRE material.

Fig. 2. Curing process at room temperature

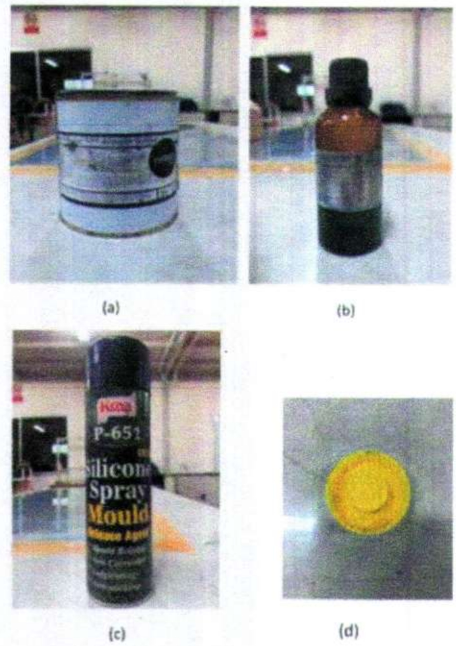

Fig. 3. The material used for fabrication (a) RTV silicone rubber (b) Hardener (c) Silicone spray (d) MRE mold

III. EXPERIMENTAL SETUP AND TESTING

The MRE device is designed to test the MRE during the impact test. As shown in Figure 4, coil bobbin, sleeve, and impactor are additional tools used to do the experimental setup of the MRE device. The fabricated MRE will be stacked into the sleeve, and the strut is put in between the MRE. The coil bobbin will be the current supply medium for the MRE.

Fig. 4. MRE testing devices (a) MRE isolator device (b) Sleeve and impactor (c) Coil bobbin

Instron Drop Impact Machine, Ceast 9350, was used to study the impact absorption capability. CEAST software was used to set the parameters for the experiment. As shown in

Figure 5, Instron DAQ and DC power suppliers were also used during this experiment. The fabricated MRE with the size of the ferrous particle of 20 μm was stacked into the sleeve and impactor and placed into the MRE impact test device. The MRE impact test device is loaded into the impact test machine, as shown in Figure 6.

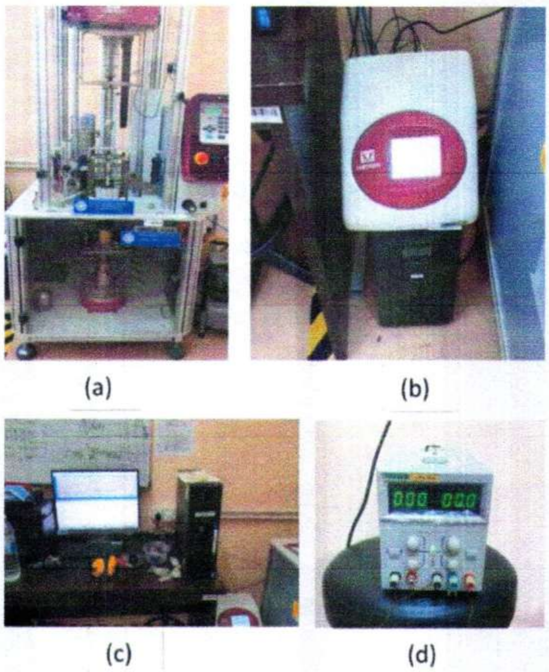

Fig. 5. Drop impact test setup (a) Impact test machine (b) Data Acquisition system (c) PC setup (d) DC supply

Fig. 6. Configuration MRE device on the impact test rig

The setup of the impact hammer is drawn up to the height of 204 mm. Then, the impact hammer is released by hydraulic. The impact hammer had an accelerometer and load cell attached to it to determine the response of the impact test. The values of the damping forces were recorded once the impact hammer hits the MRE impact test device. Each model of MRE device with different sizes of magnetic particles of 20 μm, 40 μm, and 60 μm went through the same steps five times as they were tested with five different values of current. The five different values of current are 0A, 0.5A, 1A, 1.5A, 2A. All the damping forces of MRE were recorded and tabulated for further analysis and discussion.

IV. Results and Discussion

In this study, the impact absorption device featuring MRE was developed. The MRE material was prepared composed of room temperature vulcanization (RTV) silicone rubber and carbonyl iron (CI) particles. Three models of MRE material that consisted of various carbonyl iron particle sizes of 20 μm, 40 μm, and 60 μm for impact isolator device. Then, the various type of CI particles of MRE material is used and installed to the impact absorption device for evaluating the performance of each type of MRE material using an impact drop machine [9]. The impact absorption device of MRE is tested by regulating the input current of coils from 0 A to 2 A with an increment of 0.5 A. During the experimental testing, the parameter of the drop impact machine is set based on the three parameters as listed in Table II. Three inputs were kept constant throughout the test: impact energy, impact velocity, and the falling height of the hammer. Table III shows the inputs that were kept constant throughout the test.

TABLE II. List of Parts and Materials for Laminated MRE Isolator

Part No	Part Name	Type of Material	Material	Type
1	Housing	Magnetic	Low Carbon Steel	1020
2	Steel Plate	Magnetic	Low Carbon Steel	1020
3	Coils	Non-Magnetic	Metric Copper Wire	0.8mm
4	Coil Cover	Non-Magnetic	Aluminium	1100

TABLE III. Constant Parameters during Experiment

Input Energy (J)	Impact Velocity (m/s)	Falling Height (mm)
11.00	2.0	204.00

The experimental result for the damping force of a magnetorheological elastomer with 20 μm, 40 μm, 60 μm of ferrous particles was presented in Figures 7, 8 and 9, respectively. Since the impact absorption in MRE occurs in compression mode, the graphs were plotted from 0 ms until 0.25 ms.

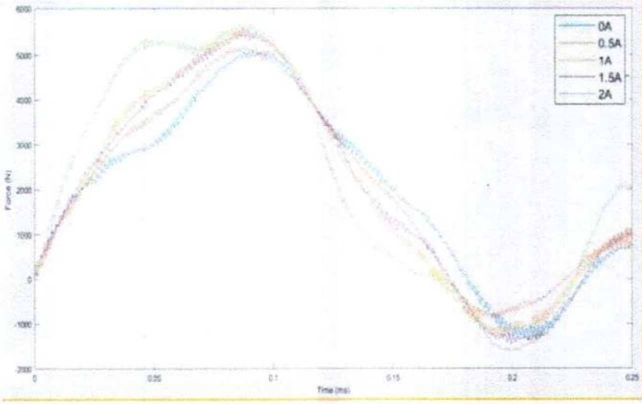

Fig. 7. Graph of Force (N) vs Time (ms) for MRE with 20 μm

The experimental results (Figure 7) show the damping force response characteristic for impact absorption devices featuring MRE under impact loading. The expected results were demonstrated for 20 μm of MRE material. The impact absorption device is tested by evaluating the device's performance in two conditions: off-state and on-state conditions. The off-state conditions did not apply any input current on the MRE coils, while the on-state condition applied the input current to the MRE coils. Based on the results obtained from experimental testing, the impact absorption device featuring MRE could produce the maximum force of 5654.76 N at maximum input current. Meanwhile, in the off-state condition, the impact absorption device could produce 5087.62N.

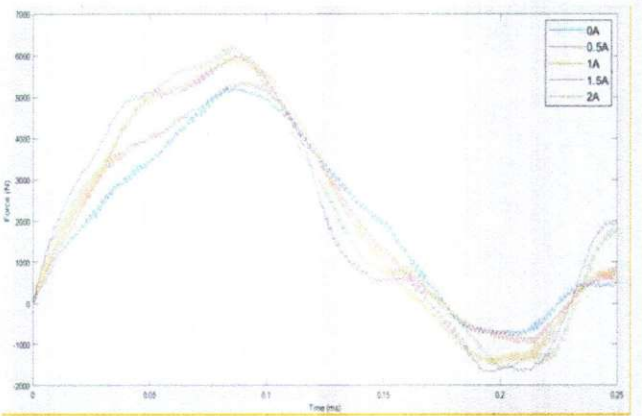

Fig. 8. Graph of Force (N) vs Time (ms) for MRE with 40 μm

The damping force characteristic of MRE material with 40 μm CI particles was exhibited in Figure 8. Two circumstances were used to evaluate the MRE material containing Carbonyl Iron particles with a diameter of 40 μm. Off-state and on-state situations are used to evaluate the device's performance. The off-state condition does not apply any input current to the MRE coils, but the on-state condition does. According to experimental data, the impact absorption device with MRE could produce a maximum force of 6205.22 N at the maximum input current. Meanwhile, the impact absorption device could produce 5254.42N in the off-state condition.

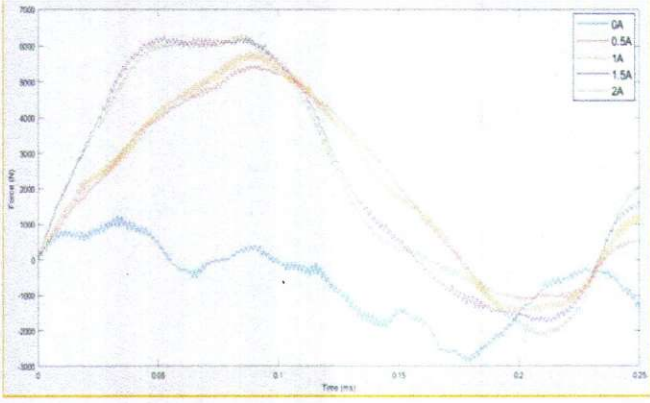

Fig. 9. Graph of Force (N) vs Time (ms) for MRE with 60 μm

Figure 9 illustrates an MRE material's damping force response characteristic when 60 μm CI particles are used. The MRE material was evaluated in two states: on-state and off-state. The off-state condition does not apply any input current to the MRE coils, but the on-state condition does. According to experimental data, the impact absorption device with MRE could produce a maximum force of 6305.31 N at the maximum input current. Meanwhile, the impact absorption device produced 1234.37 N in the off-state condition. The maximum force values for all particle sizes and currents are shown in Table IV.

TABLE IV. COMPARISON OF THE PEAK VALUE OF DAMPING FORCES

Particle size (μm)	Damping force				
	0A	0.5A	1.0A	1.5A	2.0A
20	5087.62	5187.70	5537.99	5588.04	5654.76
40	5254.42	5354.51	5854.93	6038.42	6205.22
60	1234.37	5454.59	5971.69	6271.95	6305.31

Based on the analysis referring to Table 3, the response of damping forces is influenced by the size of CI particles and the input current values. An increase in the size of the CI particles also causes a rise in the damping force. Meanwhile, the value of the input current increases, the damping force of the MRE also increases [10]. This trend shows that the applied current can control the damping force response in MRE. Magnetic flux produced by the input current increases the lateral stiffness of the MRE to obtain the desired value of damping force in MRE. Current values of more than 3A could burn the coil. Therefore the input current is regulated from 0A to 2A with an increment of 0.5A.

The value of the damping forces obtained can determine the best size of the Carbonyl Iron particle that helps dissipate the impact energy and gradual fading of the oscillation amplitude. The higher damping force increases the damping effectiveness of a mechanical system. Generally, when damping is increased in a system or structure, there will be a minimization in the vibration, sound and dynamic stresses applied [11]. The reaction force of the spring is calculated by multiplying the displacement and spring constant. A damping force is calculated by subtracting the spring reaction force from the transmitted load. However, the damping force in this test is directly obtained from the Instron data acquisition system. The obtained damping force values are further used to validate the performance of MRE in impact absorption.

Therefore, the MRE material with CI particle size of 60 μm that is tested in on-state condition with an input value of 2A shows the highest damping force response. The MRE device with 60 μm CI particles has the highest vibration damping device than the MRE devices composed with 20 μm and 40 μm CI particles. Since the MRE device with a CI particle size of 60 μm that is tested in on-state condition absorbs the highest impact energy, the desired CI particle size for maximum impact absorption is determined. The optimum size of ferromagnetic particles to absorb the highest impact energy is determined through the response of damping forces [12]. Carbonyl Iron particle with 60 μm in on-state condition absorbs the highest impact energy.

The peak damping force value of MRE material with CI particle size of 60 μm tested in the off-state condition is considered an error value in this experiment. The peak value is 1234.37 N, the lowest of other damping force values. Theoretically, the value should have been higher than the damping force values of MRE materials with 20 μm and 40 μm in off-state conditions. This trend is an unknown error, and the reason is yet to be found. Multiple tests to obtain average values could have prevented this error. Limited accessibility to the laboratory during this pandemic caused time constraints to conduct multiple tests. However, this error is neglected in the analysis of the experimental results as it does not affect the evaluation of results in determining the optimum CI particle size in MRE to achieve the highest impact absorption capability.

V. Conclusion

In this study, the properties and behaviors of magnetorheological elastomer were studied. The laminated magnetorheological elastomer isolator was designed to achieve the optimum magnetic flux density of MRE. The best current value to be injected into the MRE material and optimum magnetic flux density of the designed MRE isolator was determined using the simulation of FEMM. The best current value determined is 2A and the optimum magnetic flux density achieved is 1T. The lateral stiffness of the MRE is increased when there is a current input during the experiment.

The performance of the MRE materials was tested under impact loading. This study proves that the size of CI particles influences the response of damping force in MRE under impact loading. The higher response of damping force in MRE under impact loading attenuates the vibration in MRE. The greater size of CI particle and higher lateral stiffness can give the higher response in damping force to absorb higher impact energy. Based on the results provided, the optimum size of CI particles to absorb the highest impact energy is MRE with 60 μm CI particles in the on-state condition of 2A with 6305.31 N damping force. The response of damping force and the impact absorption capability of MRE can be increased further if more than 60 μm increases the size of CI particles. Since the scope of this study subjected to 20 μm, 40 μm, and 60 μm size of CI particles, the CI particle with 60 μm tends to be the best size in impact absorption performance.

Acknowledgment

The research has been carried out under the Fundamental Research Grant Scheme Project; FRGS/1/2021/TK02/UPNM/02/1 provided by the Ministry of Education Malaysia.

References

[1] Q. Wang, X. Dong, L. Li, and J. Ou, "Mechanical modeling for magnetorheological elastomer isolators based on constitutive equations and electromagnetic analysis," Smart Mater. Struct., vol. 27, no. 6, 2018, doi: 10.1088/1361-665X/aabdb5.

[2] Rahmat, M. S., Hudha, K., Kadir, Z. A., Nuri, N. R. M., Amer, N. H., & Abdullah, S. (2019). Modelling and control of a Magneto-Rheological elastomer for impact reduction. Journal of Mechanical Engineering and Sciences, 13(3), 5259–5277. https://doi.org/10.15282/jmes.13.3.2019.04.0430

[3] Agirre-Olabide, I., Lion, A., & Elejabarrieta, M. J. (2017). A new three-dimensional magneto-viscoelastic model for isotropic magnetorheological elastomers. Smart Materials and Structures, 26(3). https://doi.org/10.1088/1361- 665X/26/3/035021

[4] X. Song, W. Wang, F. Yang, G. Wang, and X. Rui, "Study on dynamic mechanical properties of magnetorheological elastomers based on natural rubber/thermoplastic elastomer hybrid matrix," Nanotechnology, vol. 29, no. 27, 2018.Usman, M., & Jung, H. (2015). Rheological Elastomers for Civil. January.

[5] M. S. Rahmat, K. Hudha, Z. A. Kadir, N. H. Amer, N. M. Nor, and S. B. Choi, "A hybrid skyhook active force control for impact mitigation using magneto-rheological elastomer isolator," Smart Mater. Struct., vol. 30, no. 2, 2021, doi: 10.1088/1361-665X/abd911.

[6] Liu, T., & Xu, Y. (2019). Magnetorheological Elastomers: Materials and Applications. *Smart and Functional Soft Materials*. https://doi.org/10.5772/intechopen.85083

[8] J. G. Puente-Córdova, M. E. Reyes-Melo, L. M. Palacios-Pineda, I. A. Martínez-Perales, O. Martínez-Romero, and A. Elías-Zúñiga, "Fabrication and characterization of isotropic and anisotropic magnetorheological elastomers, based on silicone rubber and carbonyl iron microparticles," Polymers (Basel)., vol. 10, no. 12, 2018, doi: 10.3390/polym10121343.

[9] Y. Li and J. Li, "Overview of the development of smart base isolation system featuring magnetorheological elastomer," Smart Struct. Syst., vol. 24, no. 1, pp. 37–52, 2019, doi: 10.12989/sss.2019.24.1.037.

[10] Metsch, P., Kalina, K. A., Spieler, C., & Kästner, M. (2016). A numerical study on magnetostrictive phenomena in magnetorheological elastomers. Computational Materials Science, 124, 364–374. https://doi.org/10.1016/j.commatsci.2016.08.012

[11] X. Guan, J. Zhang, H. Li, and J. Ou, "Semi-Active Control for Benchmark Building Using Innovative TMD with MRE Isolators," Int. J. Struct. Stab. Dyn., vol. 20, no. 6, 2020, doi: 10.1142/S021945542040009X.

[12] Van Engelen, N. C., Osgooei, P. M., Tait, M. J., & Konstantinidis, D. (2014). Experimental and finite element study on the compression properties of Modified Rectangular Fiber-Reinforced Elastomeric Isolators (MR-FREIs). Engineering Structures, 74, 52–64. https://doi.org/10.1016/j.engstruct.2014.04.046