



## Article

# Study on the Magnetic Contact Mechanical Properties of Polyurethane-Based Magnetorheological Elastomer Sealing Materials

Xiuxu Zhao <sup>1,2,\*</sup> , Emmanuel Appiah <sup>1,2</sup> and Haile Tang <sup>1,2</sup>

<sup>1</sup> School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan 430070, China; last2g2005@gmail.com (E.A.); tanghaile@whut.edu.cn (H.T.)

<sup>2</sup> Hubei Key Laboratory of Digital Manufacturing, Wuhan 430070, China

\* Correspondence: zhaoxiuxu@whut.edu.cn

**Abstract:** In order to meet the dual requirements of hydraulic dynamic sealing to ensure a reduction in friction, this study prepared polyurethane-based magnetorheological elastomers (MREs). The compression performance of isotropic and anisotropic samples under a magnetic field was tested in samples containing carbonyl iron powder (CIP) particles with different volume contents and particle sizes. The compression performance of isotropic and anisotropic samples under the magnetic field was tested under static loading, and the friction coefficient changes in isotropic and anisotropic samples under a magnetic field were analyzed by a friction testing machine. The test results show that under static compression load, the contact stress of isotropic and anisotropic specimens increases with the increase in magnetic field strength, and the magnitude of the contact stress changes when the increase in magnetic field strength is proportional to the CIP content and CIP particle size of the specimen. The friction test results of the samples showed that an increase in magnetic field strength, CIP particle diameter, and CIP content reduces the friction coefficient of the CIP particle polyurethane-based magnetorheological elastomer samples, and the variation in the magnetic friction coefficient of anisotropic samples is greater than that of isotropic samples. This research result indicates that utilizing the magneto-mechanical properties of polyurethane-based magnetorheological elastomers can provide an innovative solution to the inherent contradiction between increasing contact stress and avoiding wear in the dynamic sealing of hydraulic systems, which can provide controllable sealing performance for hydraulic dynamic sealing components in specific application scenarios, enabling them to have a better sealing ability while reducing the friction coefficient of the sealing pair.

**Keywords:** hydraulic dynamic seal; polyurethane-based magnetorheological elastomer; magnetic contact stress; magnetic friction coefficient; active regulation



Received: 27 January 2025

Revised: 8 February 2025

Accepted: 14 February 2025

Published: 16 February 2025

**Citation:** Zhao, X.; Appiah, E.; Tang, H. Study on the Magnetic Contact Mechanical Properties of Polyurethane-Based Magnetorheological Elastomer Sealing Materials. *Lubricants* **2025**, *13*, 88. <https://doi.org/10.3390/lubricants13020088>

**Copyright:** © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Hydraulic dynamic seals are indispensable components in modern fluid power systems, ensuring reliable operation by preventing leakage while accommodating relative motion between the sealing pairs. However, as these systems evolve toward higher operating temperatures and pressures, achieving an optimal balance between effective sealing and minimal friction has become a critical challenge. The lubricating oil film, which plays a pivotal role in reducing friction and wear, is often compromised under extreme conditions, leading to rapid seal failure and reduced service life [1]. This pressing issue underscores the

urgent need for innovative materials that can adapt dynamically to meet the dual demands of high-contact stress and low friction in hydraulic dynamic seals.

In practical engineering applications, to ensure the sealing effect, the contact stress between the sealing pairs is usually increased to prevent oil leakage. However, excessive contact stress can damage the continuous lubricating oil film on the sealing surface, causing an increase in friction and temperature between the sealing pairs and exacerbating sealing wear [2]. Under high-temperature conditions, the significant decrease in hydraulic oil viscosity can cause the thickness of the lubricating oil film on the sealing surface to become thinner or even disappear. At the same time, high temperatures can also cause the thermal deformation of hydraulic components, increasing the frictional resistance between sealing pairs and leading to increased sealing wear [3]. Under high-pressure conditions, an increase in sealing contact stress increases friction, resulting in a significant amount of frictional heat that causes adhesive wear between the sealing lip and the metal, thereby reducing the service life of the seal [4].

With the development of fluid power systems towards high temperature and high pressure, the rapid failure of hydraulic dynamic seals has become more prominent, becoming a bottleneck restricting the development of high-performance and long-service life hydraulic systems. How to ensure the success of the hydraulic dynamic sealing performance and improve its durability and service life is an urgent problem that needs to be solved at present. To meet the requirement of hydraulic dynamic seals to maintain higher normal contact stress while reducing friction and avoiding wear, it is necessary to further explore more suitable solutions.

Magnetorheological elastomers (MREs) are a type of smart material composed of magnetic particles and an elastic polymer matrix. Through controllable external magnetic fields, the mechanical properties of MREs can continuously and reversibly change, and it has the advantages of rapid response, controllable reversibility, and good stability. Currently, it is widely used in structural vibration control [5,6] and impact isolation [7,8]. Under the influence of a magnetic field, the dynamic mechanical properties of magnetorheological elastomers can undergo reversible changes within milliseconds [9]. Research on the magneto-mechanical properties of MRE shows that the elastic modulus [10], friction coefficient [10], and wear resistance [11] of MREs can all be changed by an external magnetic field.

Polyurethane elastomers, known for their excellent hardness range, compression permanent deformation rate, high rebound rate, and superior wetting and wear resistance, are widely used in hydraulic sealing applications [11]. By combining polyurethane with carbonyl iron powder (CIP), this study aims to develop polyurethane-based MREs with tunable magnetic and mechanical properties. Specifically, we investigate how variations in the CIP content, particle size, and alignment influence the static compression performance and friction coefficient of the material under magnetic fields. This approach not only addresses the inherent contradiction between high contact stress and low friction in hydraulic dynamic seals but also provides a novel solution for improving the sealing performance in extreme operating conditions.

The primary objectives of this study are as follows: (1) To prepare isotropic and anisotropic polyurethane-based MRE samples with varying CIP contents and particle sizes. (2) To evaluate the effects of magnetic fields, CIP content, and particle size on the static compression performance and friction coefficient of the samples. (3) To explore the potential of polyurethane-based MREs as innovative sealing materials for hydraulic dynamic seals.

The remainder of this paper is organized as follows: Section 2 describes the preparation process of the MRE samples and the experimental method used to test the static compression and friction coefficient of the samples. Section 3 presents the results and observations.

Section 4 discusses the results and their implications for hydraulic dynamic sealing. Finally, Section 5 summarizes the key findings and outlines future research directions.

## 2. Materials and Methods

### 2.1. Materials

Currently, the synthesis methods of polyurethane materials mainly include the one-step method and the two-step method (also known as the prepolymer method). The prepolymer method is the preferred method for the manufacturing of many polyurethane products [12–14], which can complete partial reactions in advance and prepare prepolymers that can be further used. Therefore, this study adopted the prepolymer method, in which the polyurethane prepolymer is a terminated isocyanate-based prepolymer (Foshan Taisheng Plastic Technology Co., Ltd., Foshan, China), the curing agent used is an MOCA (3,3'-dichloro-4,4'-diaminodiphenylmethane or di-o-chlorodiphenylmethane) (Foshan Taisheng Plastic Technology Co., Ltd., Foshan, China) with a chain expansion coefficient of 0.9, and the particle size of carbonyl iron powder is 5–10 microns (Hebei Nangong Xindun Alloy Welding Material Spray Co., Ltd., Nangong, China).

### 2.2. Sample Preparation

The preparation process of MRE specimens can be divided into two types based on the presence or absence of magnetic fields: isotropic and anisotropic [15,16]. Without an external magnetic field, the magnetic particles are uniformly distributed in the matrix, forming an isotropic structure. Under an external magnetic field, magnetic particles align to form an anisotropic MRE material along the direction of the magnetic field, forming a chain or cylindrical structure. Related studies have found that isotropic magnetorheological elastomers exhibit a more pronounced increase in their compressive modulus under the influence of a magnetic field [17], while anisotropic elastomers may form energy clusters between particles, leading to more severe damage to the elastic matrix during friction and wear [18]. Therefore, this study prepared isotropic and anisotropic MRE samples to investigate the effects of the CIP particle content, CIP particle diameter size, and particle arrangement on the magneto-strictive static compression performance, dynamic shear performance, and friction coefficient of magnetorheological elastomers samples.

As shown in Figure 1, the sample preparation process is as follows:

- (1) Preheating: Preheating operations include preheating the mold and preheating the polyurethane prepolymer. Before preheating the mold, it is necessary to spray a release agent on the inner surface of the mold to ensure the smooth demolding of the sample after molding, and then place it in a vulcanizing machine with a temperature set at 120 °C for preheating. Next, the polyurethane prepolymer is weighed in the balance and preheated in an 80 °C water bath. The purpose of preheating polyurethane prepolymers is to reduce their viscosity and enable the even distribution of carbonyl iron powder.
- (2) Mixing: This step is to weigh the corresponding mass of carbonyl iron powder and polyurethane prepolymer in proportion and stir them thoroughly, then weigh an appropriate amount of the additive and mix them together.
- (3) Bubble extraction: As the presence of bubbles in the sample can affect its performance, a vacuum defoamer is required to extract bubbles from the mixture.
- (4) First vulcanization: The mixture obtained is poured from the above steps into a preheated mold and then placed from the mold into the vulcanizing machine. The vulcanization temperature is set to 120 °C, and the vulcanization time is set to 30 min.
- (5) Second vulcanization: After the sample of the first vulcanization has cooled down, necessary trimming is carried out to remove excess parts, and then it is placed in

a drying oven for the second vulcanization. The vulcanization temperature should be maintained at 90 °C, and the vulcanization time should be 6–8 h. To ensure the accuracy of the experiment, four samples should be prepared for each set of parameters. The PU-MREs prepared in this study are shown in Table 1.

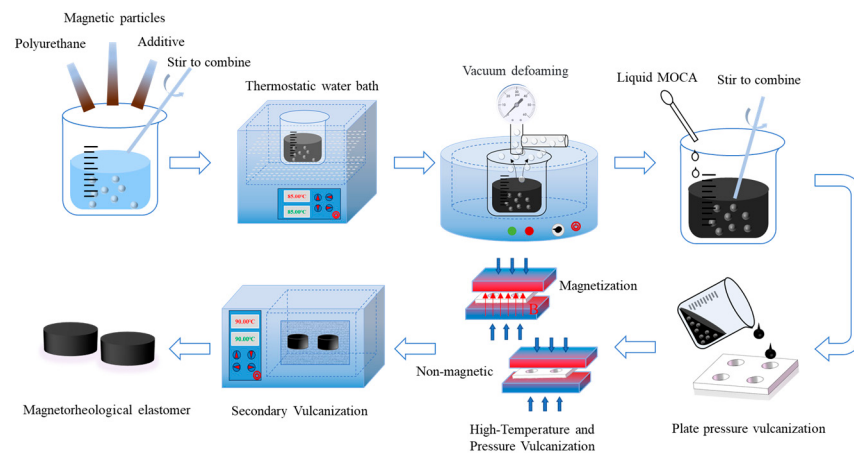


Figure 1. Sample preparation process.

Table 1. PU-MRE samples list.

| No. | Type       | CIP Content | CIP Particle Size/ $\mu\text{m}$ |
|-----|------------|-------------|----------------------------------|
| 0   | -          | -           | -                                |
| 1   | Isotropy   | 10%         | 5                                |
| 2   | Isotropy   | 20%         | 5                                |
| 3   | Isotropy   | 30%         | 5                                |
| 4   | Isotropy   | 30%         | 10                               |
| 5   | Isotropy   | 30%         | 20                               |
| 6   | Anisotropy | 10%         | 5                                |
| 7   | Anisotropy | 20%         | 5                                |
| 8   | Anisotropy | 30%         | 5                                |
| 9   | Anisotropy | 30%         | 10                               |
| 10  | Anisotropy | 30%         | 20                               |

### 2.3. Testing Methods

#### 2.3.1. Static Magnetic Compression Performance Testing

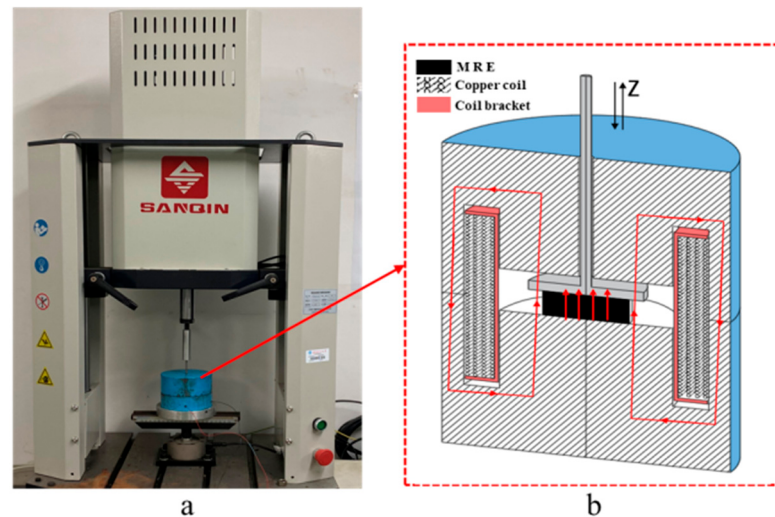
- Purpose of Testing

Hydraulic dynamic seals are subjected to pre-compression loads during actual operation, which requires the normal contact stress of the sealing pair to always be greater than the working pressure of the fluid dynamic system. Therefore, the purpose of the quasi-static magnetic compression performance testing is to investigate the influence of the CIP content and particle size on the static magnetic compression stress of polyurethane-based magnetorheological elastomers.

- Testing Method

According to the requirements of GB/T7757-2009 [19], the EDT3504 electronic fatigue testing machine with electromagnetic devices is used to conduct magnetic static compression performance tests on MRE samples. The experimental setup mainly includes a non-magnetic pressure plate, an electromagnetic coil, and a cylindrical iron block, as shown in Figure 2a. Here, the pressure plate applies compression to the sample; the electromagnetic coil provides external magnetic field force to the sample; and the cylindrical iron block is used to wrap the coil. A gap of 11 mm is reserved above and below the cylindrical

iron block to prevent the collision of the pressure plate during compression. When the excitation coil is energized, a magnetic field perpendicular to the direction of the sample is generated on the sample. The magnetic field strength is proportional to the magnitude of the current, as shown in Figure 2b. In order to reduce the impact of material deformation on the test results, it is necessary to wait 30 min at the end of each test before proceeding to the next experiment.



**Figure 2.** Static magnetic compression performance testing. (a) Testing machine; (b) magnetization device.

We performed a quasi-static compression performance test on the samples in Table 1. The sample size was  $15 \times 15 \times 4$  mm, with a static compression rate of 25% and a compression speed of 3 mm/min. When the contact stress reached 10 N, it was considered to have made contact. Before the experimental testing began, the test sample was cyclically compressed 3–4 times in a zero-field environment to eliminate the Mullins effect and obtain a stable stress–strain curve.

Under the same testing conditions, the static compressive contact stress [20] changes in the isotropic and anisotropic samples with different CIP contents and particle sizes under a magnetic field were investigated through experiments.

### 2.3.2. Magnetic Friction Coefficient Test

- Testing purpose

In this study, friction coefficient tests were conducted on the samples in both non-magnetic and magnetic field environments to analyze the effect of the magnetic field on the friction coefficient of the samples.

- Testing method

As shown in Figure 3a, the friction coefficient of the sample was tested using a ball–disc friction tester. We chose non-magnetic alumina ceramics as friction pairs to prevent them from being affected by magnetic fields during the testing process [21]. A magnetic field with a strength of 300 mT was applied by placing a permanent magnet under the sample. The load applied in the experiment was 5 N, the sliding speed was 20 mm/s, and the experimental time was 15 min, which is the time it took for the friction coefficient to stabilize, as shown in Figure 3b.

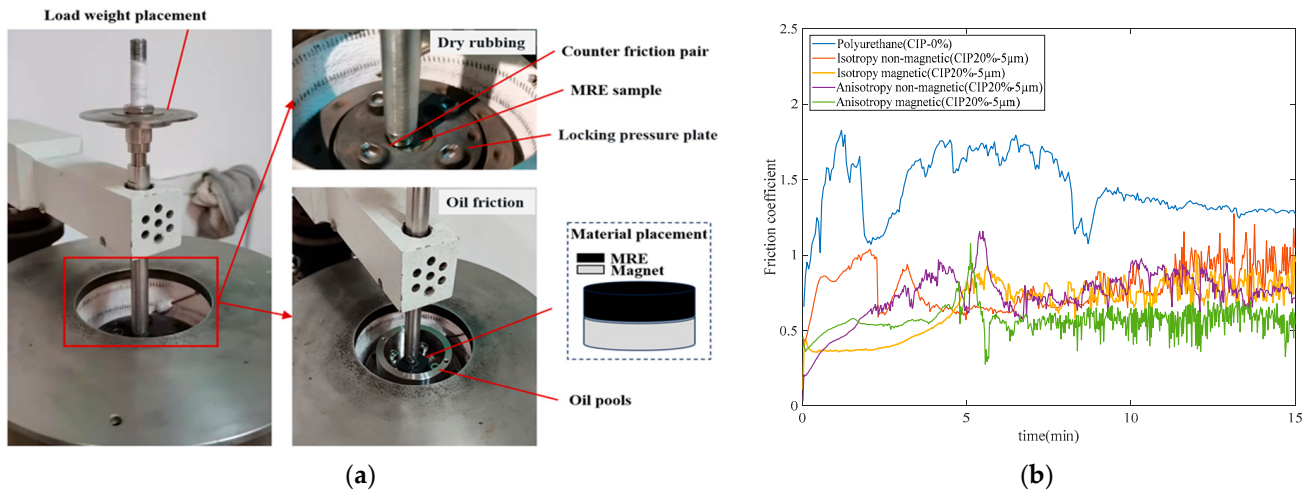


Figure 3. (a) Friction experiments. (b) COF plot for PU, isotropic and anisotropic MRE samples.

### 3. Results

#### 3.1. Static Magnetic Compression Performance Testing

##### 3.1.1. Static Compression Test Results of Isotropic Specimens

The static compression test experimental curves of isotropic specimens are shown in Figure 4a,c, and the static compression stress calculation results of the specimens are shown in Figure 4b,d. As shown in Figure 4b, with the increase in the CIP content, the static compressive stress of the sample gradually increased under the same strain. Under different magnetic fields, the static compressive stress of the sample underwent significant changes. With the increase in the CIP content, the static compressive stress of the sample first increased and then decreased. When the CIP content was 20%, the increase in the static compressive stress of the sample was relatively large, reaching 13.82%. From Figure 4d, it can be seen that under the same CIP content, the increase in static compressive stress varies for samples with different CIP particle sizes. When the CIP particle size is 10 μm, the increase in compressive stress is relatively large, with an increase of 8.05%.

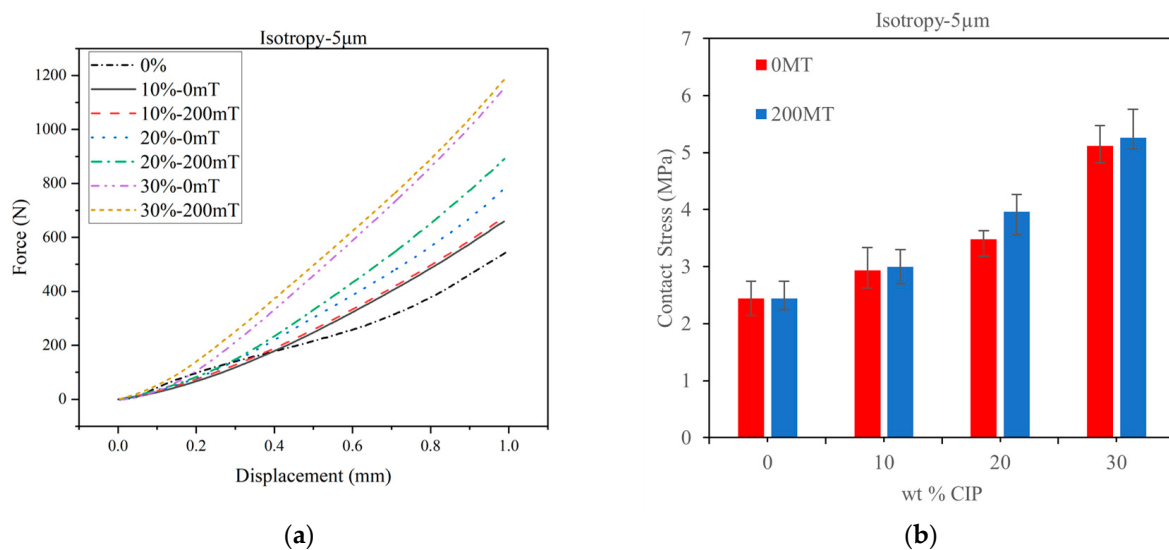
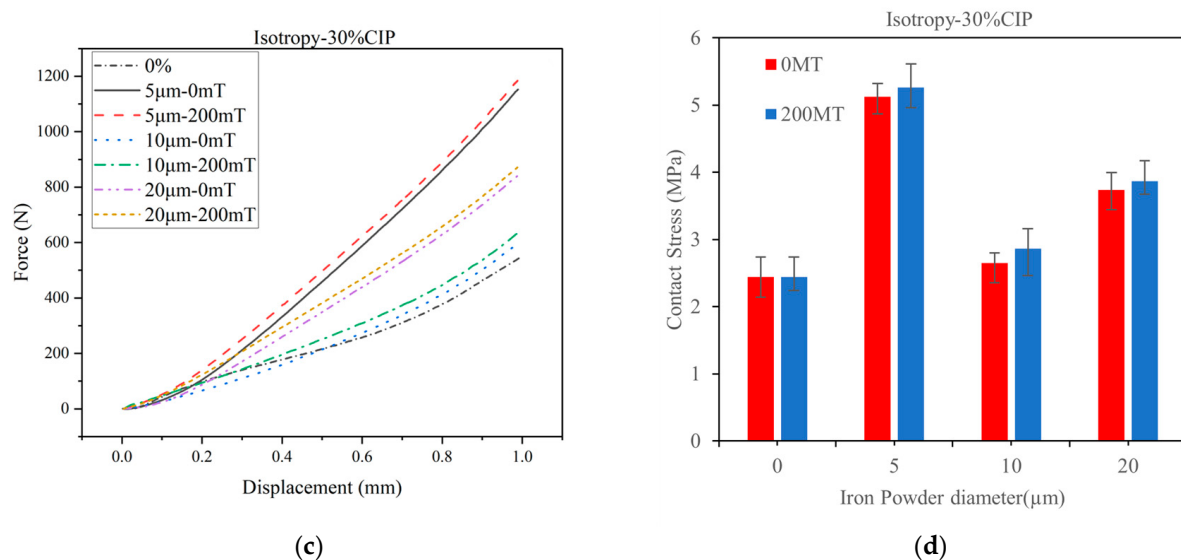


Figure 4. Cont.



**Figure 4.** Static compression test results of isotropic specimens (a) 5  $\mu\text{m}$  with varying CIP concentration and its corresponding contact stress response (b). (c) 30% CIP concentration with varying CIP sizes and its corresponding contact stress response (d).

### 3.1.2. Experimental Results of Static Compression on Anisotropic Specimen

The static compression test results of the anisotropic specimens are shown in Figure 5.

As shown in Figure 5a, the static contact stress of the anisotropic specimen increased with the increase in the CIP content at the 25% compressive strain. Compared with pure polyurethane material, the static compressive stress of the specimen with 10% CIP content actually decreased. When the CIP content was fixed at 30%, the static contact stress of the sample was observed by changing the particle size. As shown in Figure 5b, the experimental results indicate that the static contact stress of the anisotropic sample with a CIP content of 30% increased with the increase in the CIP particle size. The maximum increase in static contact stress was observed at a CIP particle size of 20  $\mu\text{m}$  (13.94%), indicating a relatively better magnetorheological effect.

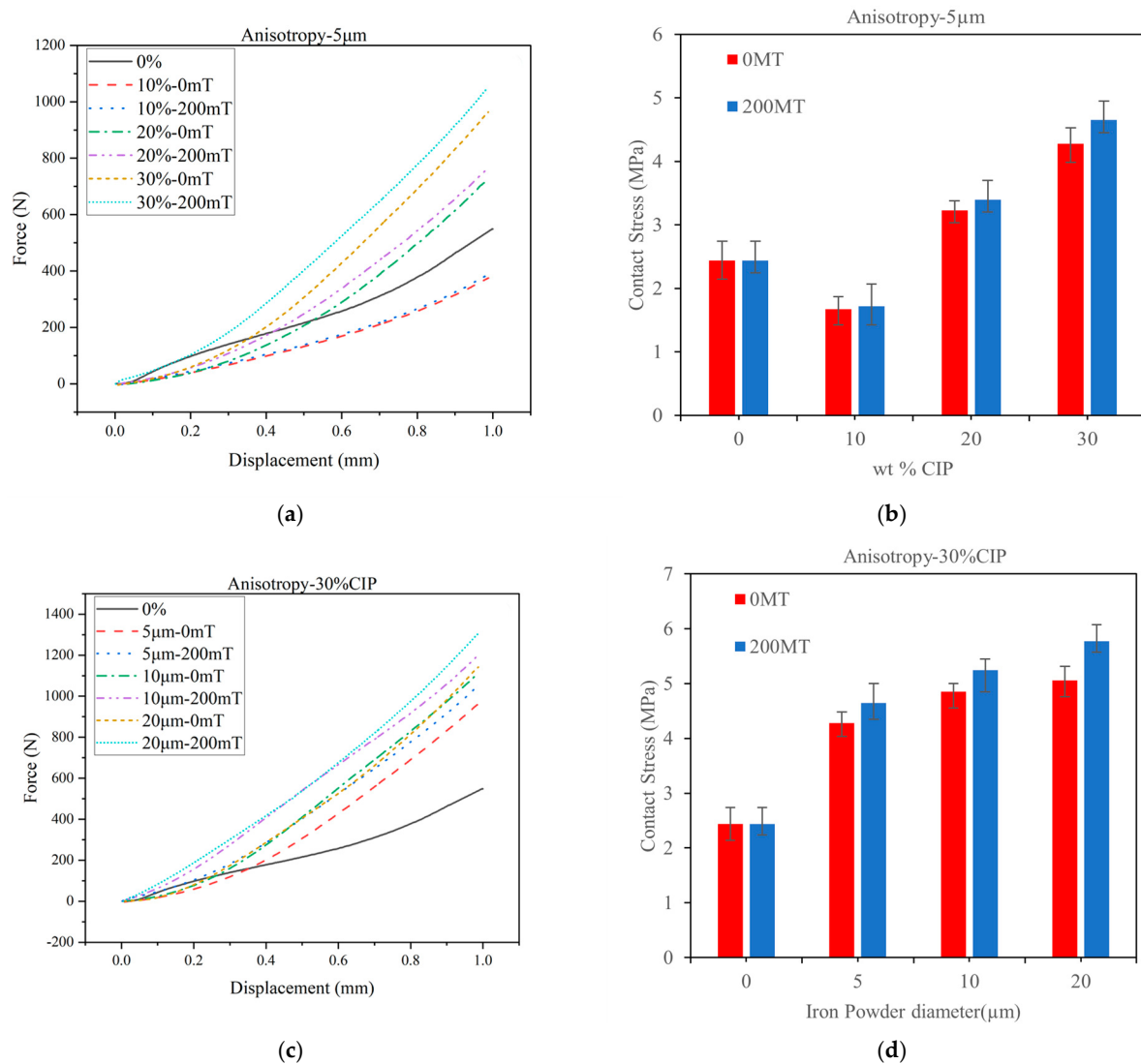
### 3.2. Magnetic Friction Coefficient Test

#### Testing Results

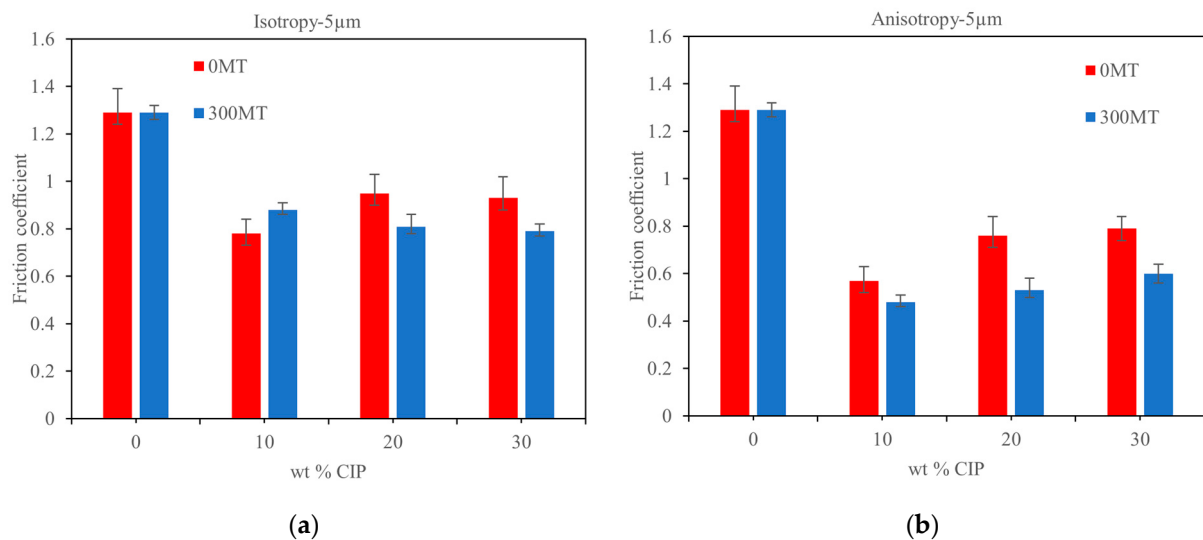
The friction coefficient test results of the samples in Table 1 are shown in Figure 6.

From Figure 6a,b, it can be seen that when the diameter of CIP particles was 5  $\mu\text{m}$ , the friction coefficients of samples with different CIP contents were lower than those of pure polyurethane samples without CIP, and the friction coefficient values of anisotropic samples were lower than those of isotropic samples. Under the influence of an external magnetic field, the friction coefficient of anisotropic samples also changed more than that of isotropic materials.

The experimental results show that the friction coefficient of polyurethane-based MREs decreased with increasing magnetic field strength, CIP content, and particle size. This finding is consistent with studies by Lian et al. (2015) [10], Lian et al. (2018) [22], and Li et al. (2020) [23], which reported similar reductions in friction coefficients for MREs under magnetic fields. The alignment of CIP particles under a magnetic field smoothens the contact surface, reducing frictional forces and wear.



**Figure 5.** Static compression test results of anisotropic specimens (a) 5  $\mu$ m with varying CIP concentration and its corresponding contact stress response (b). (c) 30% CIP concentration with varying CIP sizes and its corresponding contact stress response (d).



**Figure 6.** Friction coefficient test results of the samples (a) Isotropic 5  $\mu$ m with varying CIP concentration. (b) Anisotropic 5  $\mu$ m with varying CIP concentration.

#### 4. Discussion

The friction coefficient of the magnetorheological elastomer can be calculated using the following formula [24]:

$$f = \frac{3\pi\sqrt{R\delta}}{4E'}\alpha + \beta \quad (1)$$

where  $\alpha$  and  $\beta$  are constants, and their sizes are determined by the surface roughness and mechanical properties of the magnetorheological elastomer;  $R$  is the micro protrusion radius of the contact surface of magnetorheological elastomer;  $\delta$  is the deformation amount generated by each micro protrusion during compression deformation, and  $E'$  is the equivalent elastic modulus of the contact pair. Its calculation formula is as follows:

$$E' = \frac{1}{2} \left( \frac{1 - \mu_1^2}{E_1} + \frac{1 - \mu_2^2}{E_2} \right) \quad (2)$$

where  $\mu_1$  and  $\mu_2$  are Poisson's ratios of the magnetorheological elastomer material and the contact material, respectively, while  $E_1$  and  $E_2$  are the elastic moduli of the magnetorheological elastomer material and the contact material, respectively. When the contact material does not change, its elastic modulus  $E_2$  remains unchanged, and  $\mu_2$  also remains unchanged. Therefore, the change in the equivalent elastic modulus is only related to the elastic modulus  $E_1$  of the magnetorheological elastomer.

According to GB/T7757-2009 [19], the formula for calculating the compressive modulus of the specimen under a 25% strain condition is as follows:

$$E_{0.25} = \frac{F_{0.25}}{A\varepsilon_{0.25}} \quad (3)$$

where  $F_{0.25}$  is the force applied to generate the 25% compressive strain, in N,  $A$  is the initial cross-sectional area of the specimen, in  $\text{mm}^2$ , and  $\varepsilon_{0.25}$  is the 25% compressive strain.

According to Equation (2), the compression modulus of the sample is calculated as shown in Table 2. With the increase in the CIP content in the sample, the compression modulus of the sample material increases under the 25% strain condition. This result indicates that the reason for the increase in the static contact stress of the sample under a magnetic field is due to the increase in the compression modulus of the sample.

**Table 2.** Calculation results of magnetically induced compressive modulus of samples.

| No. | Type       | CIP Content/Vol% | CIP Particle Size/ $\mu\text{m}$ | Static Compression Modulus (MPa) |          |
|-----|------------|------------------|----------------------------------|----------------------------------|----------|
|     |            |                  |                                  | No Magnetic                      | Magnetic |
| 0   | -          | -                | -                                | 9.74                             | 9.74     |
| 1   | Isotropy   | 10%              | 5                                | 11.71                            | 12.01    |
| 2   | Isotropy   | 20%              | 5                                | 13.91                            | 15.84    |
| 3   | Isotropy   | 30%              | 5                                | 20.48                            | 21.06    |
| 4   | Isotropy   | 30%              | 10                               | 10.59                            | 11.44    |
| 5   | Isotropy   | 30%              | 20                               | 14.94                            | 15.48    |
| 6   | Anisotropy | 10%              | 5                                | 6.67                             | 6.90     |
| 7   | Anisotropy | 20%              | 5                                | 12.91                            | 13.58    |
| 8   | Anisotropy | 30%              | 5                                | 17.12                            | 18.62    |
| 9   | Anisotropy | 30%              | 10                               | 19.39                            | 21.00    |
| 10  | Anisotropy | 30%              | 20                               | 20.25                            | 23.07    |

The elastic modulus of MREs increases with a higher CIP content, larger particle sizes, and stronger magnetic fields. This increase in the elastic modulus enhances the material's stiffness, which directly contributes to higher contact stress under static compression. As

shown in Figures 4 and 5, the contact stress of both isotropic and anisotropic samples increases with magnetic field strength.

After being installed in the sealing groove, the contact surface of the sealing ring bears the contact stress  $\sigma_0$  generated by the pre-compression load as follows:

$$\sigma_0 = E \cdot \frac{\varepsilon_0}{(1 - \nu^2)} \quad (4)$$

where  $E$  is the elastic modulus of the sealing material,  $\varepsilon_0$  is the pre-compression deformation of the sealing ring, and  $\nu$  is Poisson's ratio of the sealing material [25]. After adding CIP particles, the elastic modulus  $E$  of the sealing material can be increased by applying an external magnetic field, and the sealing contact stress  $\sigma_0$  can increase accordingly, which helps to improve the reliability of the hydraulic seal. For hydraulic dynamic seals, an increase in contact stress is crucial as it ensures sufficient pressure between the sealing contact pairs to prevent fluid leakage.

## 5. Conclusions

To meet the performance requirements of hydraulic dynamic seals in terms of preventing leakage and minimizing friction, this study prepared isotropic and anisotropic polyurethane-based magnetorheological elastomer samples with different CIP contents and particle diameters. The friction coefficient and static compression performance of the samples were tested and analyzed under both non-magnetic and magnetic field conditions. The results showed the following: (1) Through the friction coefficient test of the PU-MRE sample, it was found that an increase in magnetic field strength, CIP particle diameter, and CIP content all reduce the friction coefficient of the PU-MRE sample. This result indicates that regulating the external magnetic field is expected to reduce the friction between PU-MRE sealing pairs and avoid the rapid wear of hydraulic dynamic seals. (2) The effects of magnetic field, CIP particle size, and CIP concentration on the static compression performance of isotropic and anisotropic samples were explored through the static compression performance testing of samples. The results showed that under static compression load, an increase in magnetic field strength, CIP particle diameter, and CIP content can increase the compressive stress of the PU-MRE samples, which helps improve the sealing ability.

The results demonstrate the potential of MREs as innovative sealing materials for hydraulic dynamic seals. Compared with traditional sealing materials, the main advantages of PU-MRE include the following: (1) Tunable Properties: Under an external magnetic field, the elastic modulus of MREs increases, enabling the active regulation of contact stress. This is particularly beneficial for maintaining sealing performance under high-pressure conditions. (2) Reduced Friction: The friction coefficient of MREs decreases with increasing magnetic field strength, CIP content, and particle size. In our work, we observed isotropic samples with 20% CIP content, which showed a 13.82% reduction in the friction coefficient under a magnetic field. Anisotropic samples with 30% CIP content and 20  $\mu\text{m}$  particle size exhibited a 13.94% increase in contact stress and a greater reduction in friction compared to isotropic samples. (3) Improved Sealing Ability: The increase in compressive stress under magnetic fields enhances the sealing ability of MREs, addressing the inherent contradiction between high-contact stress and low friction in traditional sealing materials.

These properties can provide controllable sealing performance for hydraulic dynamic sealing components in specific application scenarios, enabling them to have better sealing ability while reducing the friction coefficient of the sealing pair. The controllable changes in the magneto-mechanical properties of MREs provide an innovative solution to improve the performance of hydraulic dynamic seals. (1) By applying an external magnetic field, MREs can achieve both high contact stress (to prevent leakage) and low friction (to avoid

wear). (2) The ability to reversibly tune the mechanical properties of MREs makes them highly adaptable to varying operating conditions, offering a significant advantage over static materials like rubber.

Although magnetorheological elastomers (MREs) offer significant advantages, they also present certain limitations that must be addressed for effective implementation in sealing technology. (1) The implementation of this function requires the action of an external magnetic field, so it is necessary to consider how to apply the magnetic field and the additional control issues that may arise from it. Additionally, to prevent magnetic field interferences with hydraulic operations, the careful selection of materials for both the seals and the hydraulic system is essential. (2) Key concerns include scalability, cost, and long-term durability. This experiment demonstrated that high precision and expert knowledge are required to install MRE seals in hydraulic systems. Therefore, in future research, the reversible control method of polyurethane-based magnetorheological elastomers will be studied in conjunction with specific hydraulic dynamic seals, and the engineering application of this method will be promoted.

**Author Contributions:** Conceptualization, X.Z. and E.A.; methodology, X.Z.; validation, X.Z., E.A. and H.T.; investigation, H.T.; resources, X.Z.; data curation, E.A.; writing—original draft preparation, X.Z.; writing—review and editing, E.A.; visualization, H.T.; supervision, X.Z.; project administration, X.Z.; funding acquisition, X.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China, Grant No. 52375202.

**Data Availability Statement:** The data in the manuscript are available upon request.

**Acknowledgments:** We greatly appreciate the detailed and comprehensive revision suggestions provided by the reviewers.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

|      |                                                                         |
|------|-------------------------------------------------------------------------|
| PU   | Polyurethane                                                            |
| MRE  | Magnetorheological elastomer                                            |
| CIP  | Carbonyl iron powder                                                    |
| MOCA | 3,3'-dichloro-4,4'-diaminodiphenylmethane or di-o-chlorodiphenylmethane |

## References

- Cheng, G.; Guo, F.; Zang, X.; Zhang, Z.; Jia, X.; Yan, X. Failure Analysis and Improvement Measures of Airplane Actuator Seals. *Eng. Fail. Anal.* **2022**, *133*, 105949. [\[CrossRef\]](#)
- Tan, G.; Fan, Q.; Tan, F.; Wang, D.; Zhang, S. Advances in Tribology on Elastomer Sealing and Its Future Trends for the Huge Machinery. *Tribology* **2016**, *36*, 659–666.
- Cao, W.-H.; Gong, J.; Wang, H.-G.; Gao, G.; Qi, Y.; Yang, D.-Y. Numerical Simulation on Wear-Thermal-Stress Coupling Behavior of Cap-Seal Seal and Optimization Design. *J. Zhejiang Univ.* **2019**, *53*, 258–267.
- McKee, M.; Gordaninejad, F. Reciprocating Shaft Seals for High-Temperature and High-Pressure Applications: A Review. *J. Tribol.* **2018**, *140*, 032202. [\[CrossRef\]](#)
- Qian, L.-J.; Xin, F.-L.; Bai, X.; Wereley, N.M. State Observation-Based Control Algorithm for Dynamic Vibration Absorbing Systems Featuring Magnetorheological Elastomers: Principle and Analysis. *J. Intell. Mater. Syst. Struct.* **2017**, *28*, 2539–2556. [\[CrossRef\]](#)
- Hoang, N.V.; Zhang, N.; Li, W.; Du, H. Development of a Torsional Dynamic Absorber Using a Magnetorheological Elastomer for Vibration Reduction of a Powertrain Test Rig. *J. Intell. Mater. Syst. Struct.* **2013**, *24*, 2036–2044. [\[CrossRef\]](#)
- Rahmat, M.S.; Hudha, K.; Abd Kadir, Z.; Nuri, N.R.M.; Amer, N.H.; Abdullah, S. Modelling and Control of a Magneto-Rheological Elastomer for Impact Reduction. *J. Mech. Eng. Sci.* **2019**, *13*, 5259–5277. [\[CrossRef\]](#)

8. Behrooz, M.; Wang, X.; Gordaninejad, F. Performance of a New Magnetorheological Elastomer Isolation System. *Smart Mater. Struct.* **2014**, *23*, 045014. [CrossRef]
9. Gu, X.; Yu, Y.; Li, Y.; Li, J.; Askari, M.; Samali, B. Experimental Study of Semi-Active Magnetorheological Elastomer Base Isolation System Using Optimal Neuro Fuzzy Logic Control. *Mech. Syst. Signal Process.* **2019**, *119*, 380–398. [CrossRef]
10. Lian, C.; Lee, K.-H.; Lee, C.-H. Friction and Wear Characteristics of Magneto-Rheological Elastomers Based on Silicone/Polyurethane Hybrid. *J. Tribol.* **2015**, *137*, 031607. [CrossRef]
11. Parker Hannifin Corporation O-Ring eHandbook—O-Ring & Engineered Seals Division | Parker US. Available online: <https://www.parker.com/us/en/divisions/o-ring-and-engineered-seals-division/resources/oring-e handbook.html> (accessed on 8 February 2025).
12. Sun, L.; Jiang, H. Design, Preparation and Properties of Polyurethane Dispersions via Prepolymer Method. *Molecules* **2023**, *28*, 625. [CrossRef] [PubMed]
13. Huang, G.; Yang, T.; He, Z.; Yu, L.; Xiao, H. Polyurethane as a Modifier for Road Asphalt: A Literature Review. *Constr. Build. Mater.* **2022**, *356*, 129058. [CrossRef]
14. Akindoyo, J.O.; Beg, M.; Ghazali, S.; Islam, M.R.; Jeyaratnam, N.; Yuvaraj, A.R. Polyurethane Types, Synthesis and Applications—A Review. *Rsc Adv.* **2016**, *6*, 114453–114482. [CrossRef]
15. Sapouna, K.; Xiong, Y.P.; Shenoi, R.A. Dynamic Mechanical Properties of Isotropic/Anisotropic Silicon Magnetorheological Elastomer Composites. *Smart Mater. Struct.* **2017**, *26*, 115010. [CrossRef]
16. Jaafar, M.F.; Mustapha, F.; Mustapha, M. Review of Current Research Progress Related to Magnetorheological Elastomer Material. *J. Mater. Res. Technol.* **2021**, *15*, 5010–5045. [CrossRef]
17. Li, S.; Liang, Y.; Li, Y.; Li, J.; Zhou, Y. Investigation of Dynamic Properties of Isotropic and Anisotropic Magnetorheological Elastomers with a Hybrid Magnet Shear Test Rig. *Smart Mater. Struct.* **2020**, *29*, 114001. [CrossRef]
18. Erenchun, A.; Blanco, B.; Gil-Negrete, N.; Wang, B.; Kari, L. Effect of Lubrication on the Mechanical Behavior of Magnetorheological Elastomers in Compression Mode. *Polym. Test.* **2022**, *111*, 107617. [CrossRef]
19. GB/T 7757-2009; Rubber, Vulcanized or Thermoplastic—Determination of Compression Stress-Strain Properties. General Administration of Quality Supervision & Inspection and Quarantine of the People's Republic of China. China National Standardization Administration: Beijing, China, 2009.
20. Fereidooni, A.; Martins, A.; Wickramasinghe, V.; Suleman, A. Fabrication and Characterization of Highly Controllable Magnetorheological Material in Compression Mode. *J. Intell. Mater. Syst. Struct.* **2020**, *31*, 1641–1661. [CrossRef]
21. Kohutiar, M.; Krbata, M.; Escherova, J.; Eckert, M.; Mikus, P.; Jus, M.; Polásek, M.; Janík, R.; Dubec, A. The Influence of the Geometry of Movement during the Friction Process on the Change in the Tribological Properties of 30CrNiMo8 Steel in Contact with a G40 Steel Ball. *Materials* **2023**, *17*, 127. [CrossRef] [PubMed]
22. Lian, C.; Lee, K.-H.; Choi, S.; Lee, C. A Study of the Magnetic Fatigue Properties of a Magnetorheological Elastomer. *J. Intell. Mater. Syst. Struct.* **2018**, *30*, 749–754. [CrossRef]
23. Li, R.; Li, X.; Li, Y.; Yang, P.; Liu, J. Experimental and Numerical Study on Surface Roughness of Magnetorheological Elastomer for Controllable Friction. *Friction* **2020**, *8*, 917–929. [CrossRef]
24. Li, R.; Li, X.; Yang, P.; Liu, J.; Chen, S. The Field-Dependent Surface Roughness of Magnetorheological Elastomer: Numerical Simulation and Experimental Verification. *Smart Mater. Struct.* **2019**, *28*, 085018. [CrossRef]
25. Gedde, U.W.; Hedenqvist, M.S.; Hakkarainen, M.; Nilsson, F.; Das, O. *Applied Polymer Science*; Springer Nature: Berlin/Heidelberg, Germany, 2021; ISBN 978-3-030-68472-3.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.