Magnetic Properties of PDMS Based Magnetorheological Elastomer with Cobalt Additive

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Abstract. This study investigates the influence of Cobalt in magnetorheological elastomer (Co-MRE) on which the magnetic effect could be applied in soft optical electronics such as wearable and flexible sensors. Polydimethylsiloxane (PDMS) was used as a medium, and Co was used as a filler to construct isotropic MRE samples. The magnetic properties of Co-MRE are explored and compared to those of standard pure PDMS, and a Vibrating Sample Magnetometer (VSM) was used to analyze the magnetic behaviour. Based on the VSM evaluation, a curve that describes the relationships of magnetic fields (B) and the magnetic saturation, coercivity, and remanence was generated and drawn. Furthermore, it is also noticed that the addition of Co improved the conductive parameter, such as resistance response as the magnetic field was increased. The results also show that adding Co in PDMS-based MRE can aid with using force detection in sensing devices.

Keywords: PDMS · Magnetorheological Elastomer · Magnetic Property · Cobalt

1 Introduction

Extensive interest in intelligent materials such as magnetorheological elastomer (MRE) has rapidly increased. This acceleration is because an external magnetic field can alter these materials reversibly. In addition, other factors, such as electric, mechanical, stress, pH, humidity, temperature, etc., may also influence the response of these materials. MRE typically consists of magnetizable particles of micron size, matrix, and fillers(Gong et al., 2005). Due to their high saturation magnetization of metallic components, high permeability, and low remnant magnetization, carbonyl iron (CI) particles are the most often employed magnetic particles. The magnetic particles are distributed in rubber matrices, including natural rubber and silicone rubber(R. Li & Sun, 2013). Previous research has

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introduced fillers such as carbon black(Abdullateef et al., 2012), multiwall carbon nanotubes(Aziz et al., 2018), and nanowires(Antonel et al., 2015) as a viable method for improving the characteristics of MRE. These fillers have been shown to improve the MRE characteristics, namely the storage modulus, damping qualities, and MR effect. In addition to incorporating magnetic and filler particles in the matrix, a few studies have also included other particles, such as nickel and Gr(Zou et al., 2010), to further improve the electrical characteristics of MREs. Nevertheless, some researchers have enhanced MRE's mechanical and electrical qualities using Cobalt for its dual magnetic and electrical capabilities(Zainudin et al., 2020). Therefore, in this study, due to its magnetic-electric dual properties, Cobalt is employed to investigate the magnetic characteristics of PDMS-based MRE with a low concentration of Cobalt, as more research will be conducted to discover the optical properties of Co-MRE.

2 Method

2.1 Materials

The soft magnetic cobalt particles of 2μm in size used in this study were purchased from (R&M Chemicals, Evergreen Engineering, and Resources Co., Malaysia). Nanoparticles were not utilized due to their poor magnetism compared to microparticles (Palacios-Pineda et al., 2017). The base and curing agent of Polydimethylsiloxane (PDMS), type Sylgard 184 (Dow Corning Pty. LTD). A curing agent was used to harden the sample during the curing process. Cobalt is utilized for its dual magnetic and electric properties, which make it superior to graphite and nickel for soft robotics applications.

2.2 Co-MRE Fabrication and Magnetic Property Characterization

Several techniques, including hot pressing (Rizvi et al., 2011), injection moulding (Munteanu et al., 2022), depositing on substrates (Bica et al., 2014), formation of sandwich structures (Moradi-Dastjerdi & Behdinan, 2020), rapid prototyping and 4D printing (Bodaghi & Liao, 2019), can be used to fabricate polymeric smart elements. We chose a liquid-state polymer blend for simplicity and utilized the casting technique, as no specialized manufacturing equipment was required. Table 1 shows the composition of the fabricated samples. Samples are divided into 5: reference, sample 1, sample 2, sample 3, and sample 4. Each has a cobalt composition of 0, 1, 3, 5, and 7 wt%, respectively. These compositions were inspired by the work done by Cvek et al. (Cvek et al., 2020), where the author used 0, 1, 3, 5, and 7 wt% in their compositions to evaluate the optical properties of the MRE. In this work, these compositions are employed to evaluate the magnetic property of MRE with a low cobalt content so that its optical property may be determined in the future.

Co and PDMS were initially combined in a beaker at ambient temperature. Co particles were sonicated using ethanol as the dispersion medium to disrupt the Van der Waals interaction before being combined with PDMS. The mixture was then stirred for 10 min at 280 revolutions per minute to achieve homogeneity. For the sample to cure, the curing agent was added to the mixture at a ratio of 100:1% of the fabricated sample.

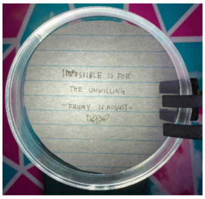
Table 1. The composition of the samples.

Sample	PDMS (wt%)	Cobalt (wt%)
Reference	100	0
Sample 1	99	1
Sample 2	97	3
Sample 3	95	5
Sample 4	93	7

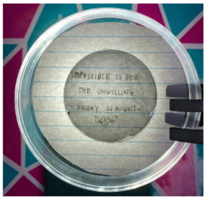
The Co-MRE mixture was then poured into a 60 mm in diameter by 1 mm thick molds. The Gr-MRE mixture was then put in a mold for curing and baked in an oven at 100 °C for 30 min(W. H. Li & Nakano, 2013; Tian et al., 2013). The Co-MRE curing procedure was carried out without magnetic fields (off-state). The components utilized to fabricate the Co-MRE are listed in Table 1.

Figure 1 depicts the manufactured Co-MRE sample for concentrations of 0, 1, 3, 5, and 7 wt% cobalt. The sample mold has a diameter of 60mm and a thickness of 1mm, as seen in the figure. The reference sample appears transparent, as shown in Fig. 1(a), indicating the absence of Cobalt. For samples 1 through 4, the sample's transparency decreases with increasing cobalt filler concentration.

The VSM is typically employed to characterize the magnetic characteristics of materials. Magnetization properties are essential for understanding how cobalt particles interact with PDMS medium and assessing whether or not the material possesses sufficient remanence for any device. Consequently, utilizing VSM, Cobalt's configuration and particle orientation have been investigated. According to Fig. 2, hysteresis loops for all MRE samples were measured in the field up to 10k Oe. At room temperature, many characteristics were investigated, including saturation magnetization Ms, coercivity Hc, and retentivity magnetization Mr. Co-MRE samples' magnetic properties were analyzed using a Vibrating Sample Magnetometer (VSM): Lakeshore, model 7412, USA. To accommodate the VSM sample holder, samples were trimmed to a diameter of around 2mm. The strength of the magnetic field was adjusted to 10,000 Oe, and a graph of magnetic field intensity vs magnetic saturation was drawn. Also given were the values for coercivity, magnetic saturation, and retentivity.

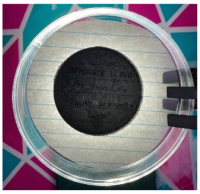


(a) Reference sample – 0 wt% of Cobalt

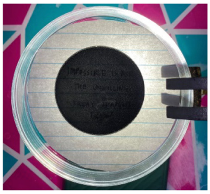


(b) 1 wt% of Cobalt

(c) 3 wt% of Cobalt



(d) 5 wt% of Cobalt



(e) 7 wt% of Cobalt

Fig. 1. Digital photograph of the fabricated Co-MRE for (a) reference sample, (b) 1 wt% - Sample 1, (c) 3 wt% - Sample 2, (d) 5 wt% - Sample 3, (e) 7 wt% - Sample 4.

3 Results and Discussion

Hysteresis refers to the phenomenon wherein magnetic induction (B) lags behind the magnetic field H. When an external magnetic field is applied to a ferromagnet like iron, the atomic dipoles align with the field. A fraction of the alignment will be preserved even when the field is removed: the material has been magnetic. Once magnetized, the magnet will retain its magnetism forever. In this study, the magnetization hysteresis curves are depicted in Fig. 2, with the MREs samples containing 7 wt% Co exhibiting the greatest Ms at 6,9931 emu/g compared to those with lower Gr content. Due to the low concentration of Cobalt utilized during sample fabrication, all samples exhibited poor magnetic saturation. The increase in magnetic saturation is nearly steady at 1.1568, 3.3701, 5.4068, and 6.9931 emu/g for 1, 3, 5, and 7 wt% Co, respectively, in these samples. These increased Ms values in Co-MRE samples incorporating filler are consistent with the findings of previous researchers, who explained the increase in magnetic saturation with adding filler concentration to MRE (Shabdin et al., 2020). Co-MRE manufactured in an isotropic environment exhibited a random distribution, allowing for greater particle mobility. Co particles tend to vibrate within MRE samples when a magnetic field is present. However, due to the particles' immobility in the medium, the particles' vibration was constrained, impeding the mobility of the Co particles.

Table 2 presents more comprehensive details on the Co-MRE samples' magnetic behaviour according to Fig. 2. The highest magnetic saturation, Ms obtained from MRE filled with 7 wt% Co, which was 6.9931 emu/g compared to 5, 3, and 1 wt% at 5.4068, 3.3701, and 1.1568 emu/g, respectively. The increment of magnetization is stable mainly because of the Co composition, which increased steadily from 1 wt% to 7 wt%.

Besides, the magnetizing field (H) needed to demagnetize the magnetic material completely, known as its coercivity, was also recorded. The coercivity, Hc of isotropic

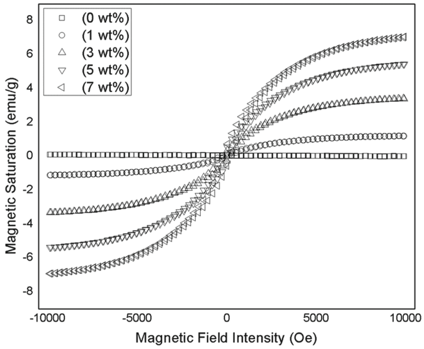


Fig. 2. VSM micrograph for 0 wt% Cobalt - reference sample, 1 wt% cobalt - Sample 1, 3 wt% cobalt - Sample 2, 5 wt% cobalt - Sample 3, 7 wt% cobalt - Sample 4.

Table 2. Coercivity, Magnetization and Retentivity of Sample.

Cobalt Conc. (wt%)	Coercivity, Hc (Oe)	Magnetization, Ms (emu/g)	Retentivity, Mr (emu/g)
0	171.04	58.667×10^{-3}	6.6088×10^{-3}
1	188.37	1.1568	89.927×10^{-3}
3	179.61	3.3701	0.26764
5	179.09	5.4068	0.41951
7	181.07	6.9931	0.54699

Co-MRE was 181.07 Oe for 7 wt% Co, while 179.09, 179.61, and 188.37 Oe for 5, 3, 1 wt% Co. On the other hand, the property of the magnetic material to retain magnetism even in the absence of the magnetizing field, known as retentivity or remanence, was also recorded. The retentivity magnetization, Mr of isotropic Co-MRE increased from 89.927 x 10^{-3} to 0.54699 emu/g, and the increment is almost stable.

4 Conclusion

In this work, Co-filled MREs were manufactured, and their magnetic properties were characterized by measuring their magnetic saturation, coercivity, and retentivity. The magnetic saturation of 7 wt% cobalt content has the maximum magnetic saturation, coercivity, and retentivity, indicating that adding Cobalt into MREs enhances their magnetic characteristics. Cobalt served as the magnetic and conductive agent in the MRE and contributed to the increase in magnetization.

5 Future Work

The Co-MRE is physically translucent, making it suitable for future optical characterization. Conductivity might also be used to describe the integrated Co. In addition, the sample might be manufactured under anisotropic circumstances to align the cobalt particles, assuming that the magnetization will rise due to the greater contact area and particles' mobility.

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