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Fabrication of Biased-Magnetorheological Elastomers (B-MRE) Based on Magnetized Ferromagnetic Particles

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ABSTRACT

Magnetorheological elastomers (MREs), like MR fluids, exploit magnetic forces between ferromagnetic particles to produce a material with instantaneously adjustable properties of stiffness and damping with external magnetic fields. In MREs, the particles are a part of a structured elastomer matrix, and an external magnetic field is applied to achieve an instantaneous change of stiffness due to magnetic forces between particles. A drawback of conventional MREs is its inability of softening (reduce stiffness) under an external field. Many engineering applications need an instant change of its stiffness in both directions, which requires a magnetic bias embedded in the MRE. One way is the use of a permanent magnet (PM) for pre-straining a base elastomer matrix, but its mechanical design can be bulky due to the size of PM. In this paper, we address a fabrication process of the biased-magnetorheological elastomers (B-MREs) and their mechanical properties. The B-MREs consist of magnetized ferromagnetic particles as fillers and an elastomer as a binder. The magnetization of ferromagnetic particles embedded in the elastomer matrix eliminates a need for the use of the PM and can achieve the desired pre-strain in the B-MRE. The experiment results related with the mechanical properties after magnetization were presented. Also, different MRE thickness and weight ratios of the ferromagnetic particles mixed with the base elastomer were compared in both normal and shear modes.

Keywords: Biased magnetorheological elastomer, variable stiffness, ferromagnetic particles

1. INTRODUCTION

Magnetorheological (MR) technology has produced a promising field of semi-active devices such as MR fluid dampers[1,2] and MR Elastomers (MREs) that have many of the benefits of fully active systems while circumventing drawbacks of active systems. MR technology relies on introducing ferrous particles within a fluid or elastomer. The properties of the fluid or elastomer are rapidly changed with the application of an external magnetic field which induces an anisotropic dipole interaction energy among the ferrous particles. Ultimately this interaction energy leads to an apparent increase in the base material's viscosity and/or modulus[3,4]. In many engineering applications, instantaneously changing the stiffness of the MRE in both directions is required, which means the MRE has an ability to instantaneously softening or decreasing stiffness as well as increasing its stiffness under the external magnetic field. Opie and Yim[5] reported the design of the biased MRE or B-MRE by applying the pre-strain to the base elastomer using a permanent magnet (PM). In this bi-directional MRE, the stiffness of the base elastomer changes depending on the direction of an external magnetic field. If the external magnetic field opposes or cancels the magnetic field of the PM, the MRE can be softened. One main drawback of the B-MRE is the use of a bulky PM for pre-straining the elastomer. It should be noted that the same softening effect can be obtained by instantly decreasing the external magnetic field of the conventional MRE, but this approach can waste the power or a battery of the MRE for maintaining a pre-strained state. The use of the PM enables the pre-straining of the base elastomer without the external electromagnetic field.

Rigbi et al. first reported the design of the MRE[3,6], and Jolly et al. modeled the behavior of magnetorheological materials[7]. Gokturk et al. made thermoplastic elastomer incorporated with ferromagnetic powders[8]. The thermoplastic elastomer was used as the binder and iron powders and nickel-iron powders as filler. The nickel-iron powders consisted of 80% of nickel and 20% of iron. Dyke et al. Borcea et al. studied the macroscopic magneto-mechanical behavior of composite materials consisting of a random, statistically homogeneous distribution of ferromagnetic, rigid inclusions embedded in a non-magnetic elastic matrix[9]. Ginder et al. have used MR elastomers as a compliant element of a single-degree-of-freedom spring-mass system with a resonant frequency that is broadly tunable by the application of a magnetic field[10]. Lerner et al. determined the vibration absorption characteristics of the MREs[11]. As mentioned previously, the conventional MRE has a difficulty of lowering its stiffness under external magnetic field unless a constant current is supplied for its pre-strain. The pre-strain of the MRE can be achieved using a permanent magnet (PM). If the external

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electromagnetic field is applied in the opposite direction of the one of the PM, the stiffness of the MRE is decreased or softened. Opie et al. developed a vibration isolator using the B-MRE [5,12]. They also developed real-time control system [13]. Trabia et al. also studied the B-MRE and validated with experiments [14]. Yang et al. developed multi-layer MRE isolator for suppression of building vibrations under seismic events [15,16]. Sun et al. studied an adaptively tuned vibration absorber based on multilayered MR elastomer including a permanent magnet layer [17]. Even though the concept of the B-MRE has been advanced from the conventional MRE, the B-MRE has the main drawback of a bulky and heavy overall package due to PM inside.

The main contribution of the paper is for replacing the PM inside of the B-MRE by embedding magnetized ferromagnetic particles. Embedding the magnetized particles to the B-MRE can make an overall design much more compact and light and expect more fast response time. The B-MREs were fabricated by mixtures of ferromagnetic particles and silicone polymer resin with different weight ratios of the filler and the binder. Different methods of mixing ferromagnetic particles with elastomers during curing have been conducted as well as magnetization. Dynamic mechanical properties of each B-MREs before and after magnetization were compared to study different fabrication processes using the dynamic material analyzer (DMA).

2. PRINCIPLES

2.1 Principles

Figure 1 shows the comparison of different types of the MRE. The B-MRE based on magnetized ferromagnetic particles does not need the permanent magnet because the ferromagnetic particles are already magnetized. The main challenge is how to magnetize ferromagnetic particles mixed and cured with the silicon base material.

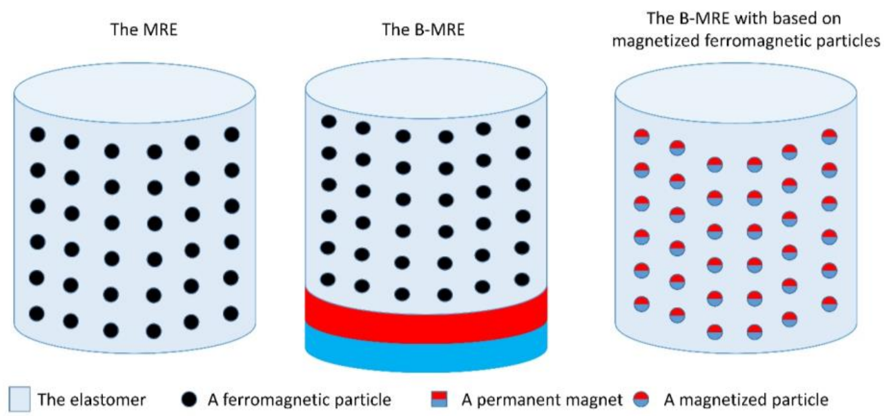


Figure 1. Comparing among the MRE, B-MRE, and B-MRE with magnetized ferromagnetic particles

In the electromagnetism, the magnetic field intensity or strength, **H,** is generated when electrons move[18]. The **H** is measured in a unit of electric current in the SI unit, Ampere/meter[19]. The **H** is defined as

$$\oint_C \boldsymbol{H} \cdot d\boldsymbol{s} = \oint_S \boldsymbol{J} \cdot d\boldsymbol{a} + \frac{d}{dt}\oint_S \epsilon_0 \boldsymbol{E} \cdot d\boldsymbol{a} \tag{1}$$

where C is the contour, S is the surface, **J** is the current density, **E** is electric field intensity, and **a** is the area vector[19].

The magnetization field, **M,** is the vector field of the density of the magnetic dipole moment. [20] The **H** is a unit of electric current in SI unit, A/m, and the **M** is defined as

$$\mathbf{M} = \mathrm{N}\mathbf{m} \tag{2}$$

where the N is the number of dipoles per unit volume, and the **m** is the moment vector[19].

The magnetic field density, **B** is a unit of Tesla (T) in the SI unit[18], and the unit of Tesla is equivalent to (N·s)/ (C·m) when N is Newton, s is second, and C is coulomb. The relationship among the **B, H,** and **M** becomes,

$$\mathbf{B} = \mu_0(\boldsymbol{M} + \boldsymbol{H}) = \mu_m \boldsymbol{H} \tag{3}$$

where the μ_0 is the permeability of air and the μ_m is the magnetic permeability[19]. The equation shows that electric current and a ferromagnetic material lead to the magnetic field density, which generates a magnetic force between ferromagnetic particles.

When the magnetic field density **B** is applied in the MRE, the shear strain of the MRE, σ is

$$\sigma = \frac{\phi\epsilon(4-\epsilon^2)J_P^2}{8\mu_1\mu_0 h^3(1+\epsilon^2)^{7/2}} \tag{4}$$

where ϕ is the volume fraction of particles in the MRE, ϵ is the scalar shear strain of the particle chain, J_p is the dipole moment magnitude per unit particle volume in units of Tesla, μ_1 is the relative permeability of the elastomer between two dipole particles, h is an indication of the gap between the particles[7,21]. In equation (4), the ϕ, μ_1, μ_0 and h are fixed material properties. The values are determined in the fabrication process. On the other hand, the J_p is variable which is determined by external magnetic field or magnetization.

Experimentally, the actual ϵ is 0.01~0.02 in the MREs, so $\epsilon^2 \cong 0$ because it is too small. Therefore the shear strain of the MRE, σ , becomes [22–24],

$$\sigma \cong \frac{\phi\epsilon J_P^2}{2\mu_1\mu_0 h^3} \tag{5}$$

The preyield modulus G becomes,

$$G \cong \frac{\sigma}{\epsilon} \cong \frac{\phi J_P^2}{2\mu_1\mu_0 h^3} \tag{6}$$

As shown in the equation (6), the modulus is controllable with the magnetic field [7].

3. FABRICATION

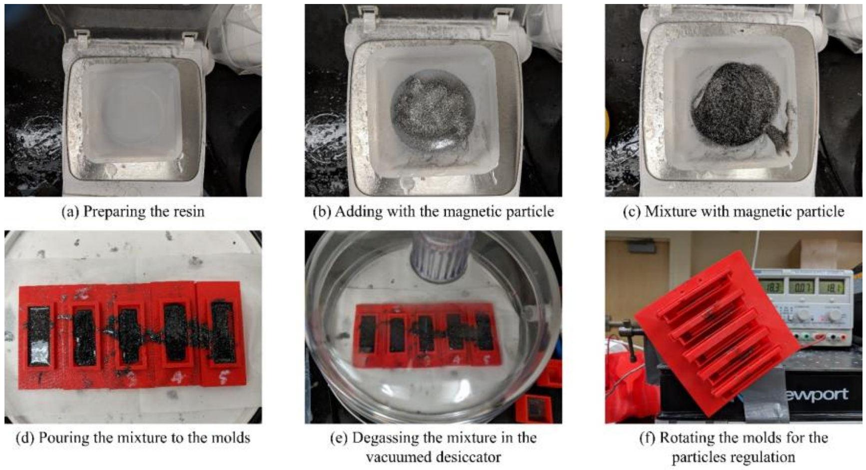
3.1 Materials

In this research, Ecoflex 00-50(Smooth-on, Inc.) was used as the elastomer. The Ecoflex 00-50 is platinum-catalyzed silicone rubber. The Ecoflex 00-50 has reasonable tensile modulus for the topic and cured in the room temperature and has less than 0.001inch/inch shrinkage[25]. For the ferromagnetic material powder, MQP-15-7-20065 (Magnequench International, LLC) was used. It is an alloy of neodymium, praseodymium, iron, and boron. The MQP-15-7-20065 has a high residual inductance and a low intrinsic coercivity[26]. It has less than 0.1% weight ratio of particles which is larger than 40 mesh (420×420μm), less than 25% weight ratio of particles which is larger than 60 mesh (250×250μm), and less than 12% weight ratio of particles which is smaller than 270 mesh (53×53μm).[26]

3.2 Fabrication process

In this study, different samples were prepared to compare their mechanical properties depending on the different mixing ratios of the resin and the ferromagnetic powders as well as the thickness of the sample. First, we made a mixture of the Ecoflex 00-50 part A, part B, and the ferromagnetic powder. (Figure 2(a) and (b)) The weight ratio of part A and B is 1:1. After that, we added the Silicone Thinner (Smooth-on, Inc.).

The weight of the thinner is 10% of the total resin weight for easier gas elimination. The mixture was stirred (Figure 2(c)), and poured it to a 3D printed molds which have the shape of the specimen (Figure 2(d)). The molds were located in a desiccator, and the internal area of the desiccator became vacuumed for degassing. (Figure 2(e)) Then, a cover was put on the mold, and the mold was overturned to prevent the ferromagnetic particles to settle down by gravity. Finally, the molds were rotated in a roller, which rotates 80 rpm, to regulate divergence of the ferromagnetic particles in the resin and waited four hours to cure the mixture. (Figure 2(e))



(a) Preparing the resin (b) Adding with the magnetic particle (c) Mixture with magnetic particle

(d) Pouring the mixture to the molds (e) Degassing the mixture in the vacuumed desiccator (f) Rotating the molds for the particles regulation

Figure 2. Fabrication for the MREs

Figure 3 shows a sectional view of the MRE. The MRE has a 50% weight ratio of the ferromagnetic particle. The white circle is a part of the larger ferromagnetic particle, and the yellow rectangle is a part of the elastomer with small ferromagnetic particles. The ferromagnetic particles are not concentrated in the partial area but mixed regularly.

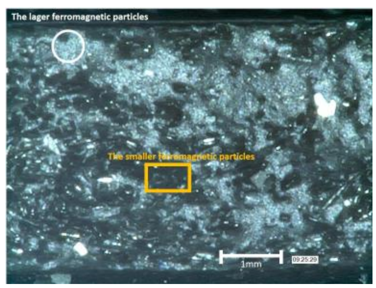
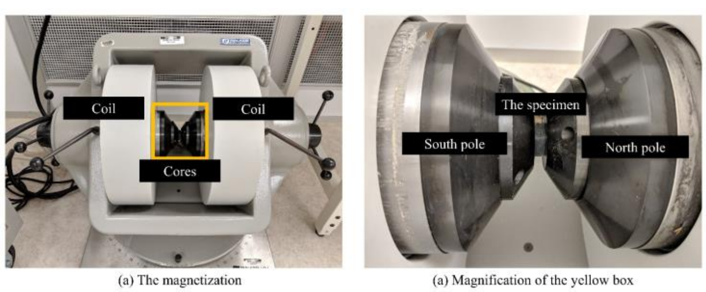


Figure 3. A sectional view of the MRE (50% weight ratio of the ferromagnetic particle)

For magnetization of the ferromagnetic particles embedded in the specimen, the model HV-10H by Walker Scientific is used. This laboratory electromagnet generates a highly uniform magnetic field, and it is shown in Figure 4(a). This electromagnet has two 25.4cm (10 inches) poles and can provide 20,500 Gauss when 75A current is applied between a 2.54cm (1 inch) air gap. A power supply HS-1050-4SS supplies the current to the electromagnet. We located the MRE sample between the poles of the electromagnet as shown in Figure 4(b). Then we set the power supply to provide 120V voltage and 50A current for 5 minutes. We measured the magnetic field density of the B-MRE with a Gauss meter (F.W. Bell 5180 Gauss/Tesla meter, OECO LLC) to confirm the MRE was magnetized. The magnetic field density is 54G at a specimen of 1mm thickness and 50% weight ratio of the ferromagnetic particles. The 1mm thicker the specimen is, the 19.6G more the magnetic field density is increased.

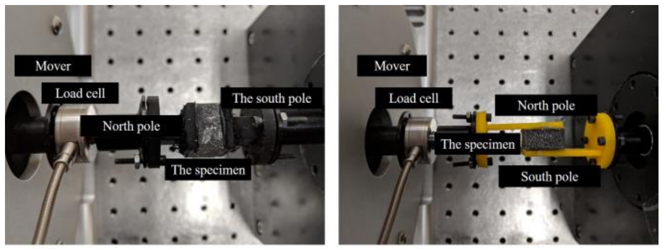


(a) The magnetization (a) Magnification of the yellow box

Figure 4. The magnetization of the ferromagnetic particles with the HV-10H electromagnet.

4. EXPERIMENTAL RESULTS

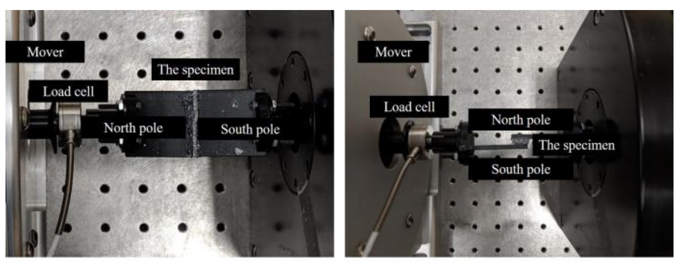
A point of the experiments is the changes in mechanical properties after the magnetization. Independent variables of the experiments are two, the first one is the weight ratio of the ferromagnetic powder and the second one is the thickness of the specimen. The measured mechanical properties are Young`s modulus or shear modulus and the damping ratio. The specimens to determine the proper weight ratio of the ferromagnetic powder have 20mm (width) x 20mm (length) with a thickness of 10mm. The weight ratios of the ferromagnetic powder for each of the specimens are changed between 10% and 60% with a 10% increment. Figure 5 and 6 show an experimental setup using the dynamic mechanical analyzer (Electroforce LM1 TestBench, Bose Corporation).



(a) The Young's modulus measure (b) The shear modulus measure

Figure 5. Mechanical properties measure depending on the weight ratio of the ferromagnetic powder

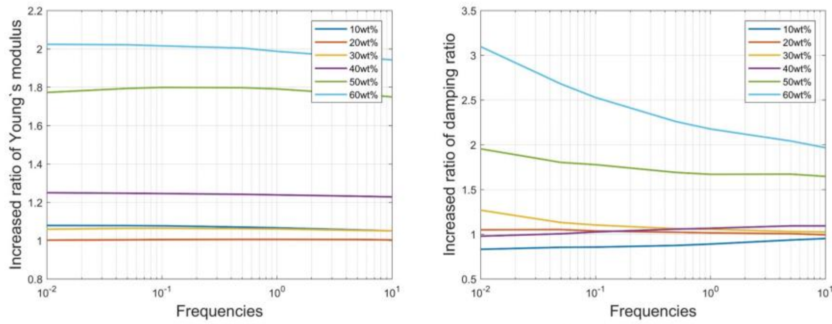
To study the effect of the specimen's thickness on magnetization, the specimens of 35mm (width) x 10mm (length) with different thickness of 1mm~5mm were used. The weight ratio of the ferromagnetic powder was fixed as 50%. Frequencies of displacements applied to measure the dynamic mechanical properties are 0.01, 0.05, 0.1, 0.5, 1, 5 and 10 Hz with a 10% strain in room temperature.



(a) The Young's modulus measure (b) The shear modulus measure

Figure 6. Mechanical properties measure depending on the thickness of the specimen

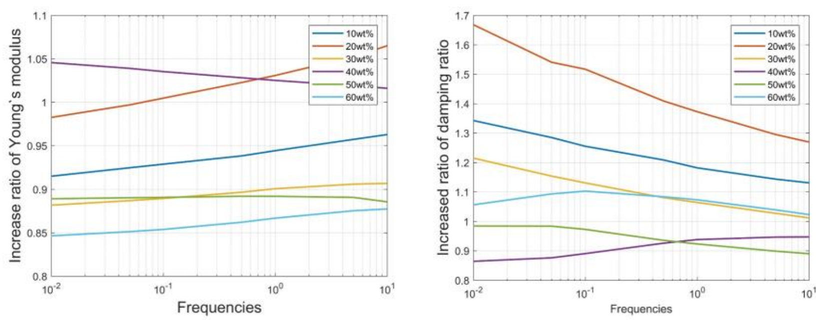
Figure 7 shows increased ratios of Young's modulus and damping ratio after the magnetization for different weight ratios of the ferromagnetic powder. As shown in Figure 7, 50% and 60% weight ratios are the most proper weight ratio of the ferromagnetic particles for the B-MRE with magnetized ferromagnetic particles. It means that they have wider ranges for controllable stiffness and damping ratios. Even though the MRE with 50% weight ratio has fewer changes than with 60% weight ratio, it also has a meaningful incremental ratio of the Young's modulus and damping ratio. According to the experimental experience, a 60% weight ratio of the ferromagnetic powder is the largest ratio to make a regular mixture of the ferromagnetic powder and the resin.



(a) Young's modulus (b) The damping ratio

Figure 7. The increased ratio of Young's modulus and damping ratio depending on the weight ratio of the ferromagnetic powder

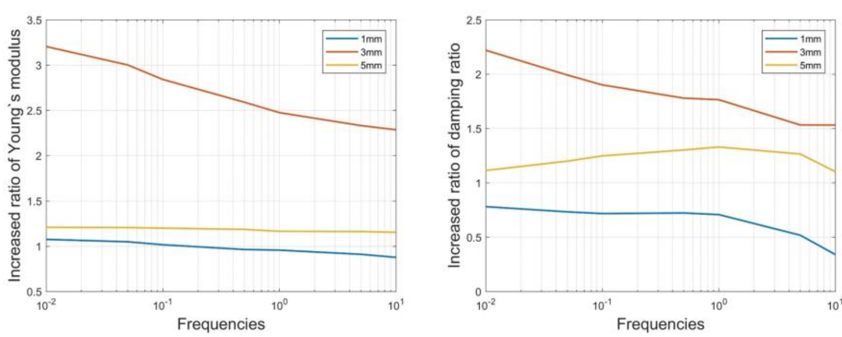
Figure 8 shows the increased ratios of the shear modulus and damping ratio after the magnetization depending on the weight ratio of the ferromagnetic powder. The results of shear modulus depending on the weight ratios are meaningless because the increased ratios are too small.



(a) Young's modulus (b) The damping ratio

Figure 8. The increased ratio of the shear modulus and damping ratio depending on the weight ratio of the ferromagnetic powder

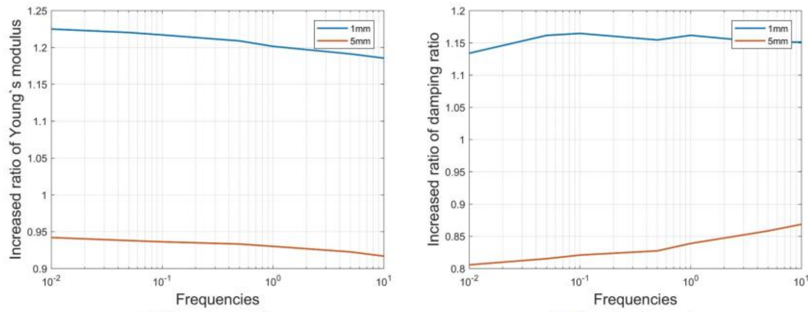
Figure 9 shows the increased ratios of the Young's modulus and damping ratio depending on the thickness of the specimens. The result shows that 3mm thickness has the largest increased ratio. If the thickness is too thin, there is not enough magnetic density flux to attract the particles each other. If the elastomer is too thick, on the other hand, the ferromagnetic particles are less magnetized. Even though the particles do not attenuate the magnetic density flux, because, the elastomer area does it. Therefore the 3mm thickness is optimized thickness.



(a) Young's modulus (b) The damping ratio

Figure 9. The increased ratio of Young's modulus and damping ratio depending on the thickness of the specimens (selected results)

Figure 10 shows the increased ratio of the shear modulus and damping ratio depending on the thickness of the specimens. The results of shear modulus depending on the thickness are also meaningless because the increased ratios are too small as the previous experiment. Because the magnetized particle attracts each other and the attraction force is maximized when the overlayed area of the two particles are maximum. The normal force maintains the overlayed area, but the shear strength declared the overlayed area, so the attraction force is decreased. For the same reason, more force is needed when two attached magnets are separated with pulling two magnets on the opposite direction than shearing the two magnets.



(a) Young's modulus (b) The damping ratio

Figure 10. The increased ratio of the shear modulus and damping ratio depending on the thickness of the specimens (selected results)

5. CONCLUSIONS AND FUTURE WORKS

In this paper, the procedure of embedding and magnetizing the ferromagnetic particles in the MRE was presented, and their mechanical properties were compared in terms of the weight ratio of the ferromagnetic powder and the thickness of the B-MREs. It was found that the proper weight ratio of the ferromagnetic powder is 50%~60%, and the thickness for the B-MREs based on the level of magnetization of the ferromagnetic particles is around 3mm. It was also found that applying forces in the same direction as the magnetic field provides the largest controllable Young's modulus changes. The proposed B-MRE can be designed much lighter and compact compared with the one with the PM, and provide many design options for many engineering applications. In the future, both transient and steady state behaviors of the sample will be experimentally determined to find out appropriate engineering applications of the device.

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