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Iron particle and anisotropic effects on mechanical properties of magneto-sensitive elastomers

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ABSTRACT

Rubber specimens were prepared by mixing micron-sized iron particles dispersed in room-temperature-vulcanized (RTV) silicone rubber by solution mixing. The possible correlations of the particle volume, size, and distribution with the mechanical properties of the specimens were examined. An isotropic mechanical test shows that at 60 phr, the elastic modulus was 3.29 MPa (electrolyte), 2.92 MPa (carbonyl), and 2.61 MPa (hybrid). The anisotropic effect was examined by curing the specimen under magnetic fields of 0.5–2.0 T at 90° relative to the applied strain. The measurements show anisotropic effects of 11% (carbonyl), 9% (electrolyte), and 6% (hybrid) at 40 phr and 1 T. At 80 phr, the polymer-filler compatibility factor (c-factor) was estimated using the Pythagorean theorem as 0.53 (regular) and 0.73 (anisotropic studies). The improved features could be useful in applications such as controlled damping, vibrational absorption, or automotive bushings.

1. Introduction

Magneto-sensitive specimens have been studied since 1948 with Rabinow's pioneer work on magneto-fluids (MFs) [1]. In recent decades, there has been consistent attention on MFs for various applications [2–4]. There has also been considerable focus on magneto-sensitive elastomers (MSEs) as a new class of materials [5,6]. Such smart materials have micron-sized iron particles dispersed in an elastomeric matrix [6,7]. Generally, it is advantageous to use MSEs over MFs because the suspended magnetic particles in MSEs do not settle over time.

MSEs exhibit isotropic or anisotropic features that depend on exposure to a magnetic field. These materials show Newtonian-like behavior in the absence of a magnetic field and anisotropic characteristics in the presence of a field. The most fundamental applications for MSEs are controlled damping, vibrational absorption applications, and automotive bushings [8].The anisotropic behavior is due to the orientation of filler particles in the rubber matrix. Depending on the direction of the magnetic field, the orientation of the filler particles can be parallel ($\delta = 0°$), angled ($\delta = > 0°$ to <90°), or perpendicular ($\delta = 90°$) to the applied strain (Fig. 1).

The mechanical stiffness in MSEs depends on the formation of microstructures during curing [9]. Various studies show that single or hybrid filler systems can be used to achieve balanced properties [10,11]. A few studies present specimens containing iron particles as a filler to develop low-cost final products with improved properties [9]. The properties of a hybrid system are enhanced by the interaction effects of filler particles or by efficient filler networking in the rubber matrix [12]. Recently, Boczkowska et al. used three types of iron particles with various sizes (1–70 μm) in a rubber matrix to obtain improved properties [13]. The properties depend on the amount of filler, polymer-filler compatibility, magnetic field amplitude, interfacial interaction, and aspect ratio of the filler [11,12,14,15]. The effects of the fillers and their interactions with polymer chains play an important role in determining the overall properties in nanocomposites.

The mechanical stiffness strongly depends on the volume, size, shape, and orientation of filler particles under a magnetic field [13]. During viscoelastic behavior of a specimen under static or cyclic strain, a part of the energy is stored and part is lost as dissipated heat [16]. The dispersion and orientation of filler particles in the rubber matrix are well known to be influenced by the structural features of the nanofillers [12,16]. Various studies on MSEs use different types of iron particles. However, these studies were limited to investigations on filler dispersion, modeling of MSEs, and orientation of the filler particles under different magnetic fields [13–15]. Few studies have examined reinforcement, interaction factors in theoretical models for two-component systems, dissipation losses, or filler flocculation. There is also very little work on RTV silicone rubber reinforced with micron-sized iron particles.

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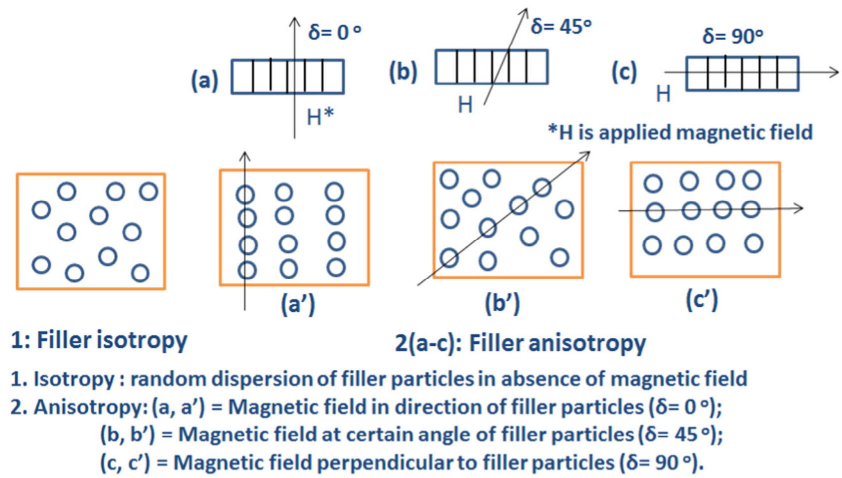

Fig. 1. Filler isotropy and anisotropy in magneto-sensitive elastomers.

RTV silicone rubber deserves attention due to its use in a wide range of applications, such as actuators.

The present work looks at these properties of specimens based on RTV silicone rubber. The possible correlations of the filler's particle volume, size, and distribution with the mechanical properties were estimated. Micro-sized carbonyl and electrolyte filler particles and their hybrids with different ratios were dispersed in a rubber matrix. The fillers were used in a pristine form as an environmentally friendly method to be used at an industrial scale. The properties of the MSE specimens were also examined for their anisotropic effects.

2. Experimental

2.1. Materials

RTV silicone rubber (KE-12; viscosity = 100 poise at 25 °C, Shin-Etsu Chemical Corporation Ltd., Japan) was used as the matrix with a hardener (CAT-RM, Shin-Etsu Chemical Corporation Ltd., Japan). Carbonyl type (S1640, ISP technologies Inc., USA) and electrolytic type (Fe#400, Aometal Corporation Ltd., Korea) micron-sized iron particles were dispersed in the matrix. All materials were used in their pristine form, and further purification was avoided. Other characteristics of the fillers provided by the supplier are summarized in Table 1.

2.2. Preparation of nanocomposites

The specimen preparation began by normalizing the RTV silicone rubber for 30 min [10]. The filler particles were then dispersed in the rubber by solution mixing using the formulations shown in Table 2. Mixing was carried for 5–8 min until a homogenous phase was achieved. In the next step, the specimen was placed in a vacuum for 10–12 min to remove air. A known amount of hardener was then added and mixed for ~1 min until a homogenous phase was achieved. Finally, the rubber specimens were transferred to a cylindrical mold (20 × 10 mm) and kept in ambient conditions to dry before testing.

Table 1
Fillers characteristics.

Characteristics	Carbonyl	Electrolytic
Average particle size	3–5 μm	7–11 μm
Shape	Oval	Rod-shape
Color	Brownish	Light greyish
Density (g/cm^3)	2–3	2–3
Iron (%)	98.1	98.8
Carbon (%)	0.8–1	0.1–0.2
Oxygen (%)	0.35–0.5	0.15–0.3
Nitrogen (%)	0.5–0.7	0.1–0.2

2.3. Characterization techniques

Mechanical tests were performed to obtain the elastic modulus and compressive profiles under a dynamic load of 0.5 kN up to 35% strain at a strain rate of 1 mm/min using cylindrical samples (20 × 10 mm). The ultimate properties of the specimen were examined through tensile tests under a dynamic load of 0.1 kN on dumbbell-shaped specimens with 2-mm thickness at a strain rate of 50 mm/min. Mechanical tests were performed using a universal test machine (Lloyd Instruments, West Sussex, UK). The anisotropic effect was determined by studying the specimen under variable magnetic fields of 0.5–2.0 T. The details of the setup are shown in Fig. 2.

3. Result and discussion

3.1. Properties of vulcanizates

3.1.1. Isotropic mechanical properties

The isotropic compressive strength was studied through the profiles obtained without a magnetic field. There was an increase in the compressive load as the filler loading increased (0 to 100 phr), as shown in Fig. 3a. This increase is attributed to the increasing stiffness in the specimens due to the increasing volume fraction of the filler. Another possible explanation is that the distribution improved the contact among interacting components and led to efficient filler networking [12,17–19]. Farshad and Benine achieved a maximum strain capacity of about 40% with a specimen containing randomly dispersed particles [18].

The profiles of mechanical tests at 60 phr of filler (electrolyte, carbonyl, and hybrids) are shown in Fig. 3b. The electrolyte-based specimen shows higher load-carrying capacity than the hybrid and carbonyl specimens. This is attributed to the efficient stress transfer from the polymer chains to the filler flocs with increasing strain in the electrolyte filler specimens [20,21]. The elastic modulus is plotted as a function of filler content in Fig. 3c. The electrolyte filler specimen shows a higher modulus than the carbonyl and hybrid filler systems. For example, at a filler content of 60 phr, the elastic modulus was 3.29 MPa (electrolyte), 2.92 MPa