**Magnetorheological Effect of Magnetic Gels Containing Fe$_2$O$_3$**

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The relationship between the diameter or the number density of magnetic-particle columns and the magnetorheological effect has been investigated using carrageenan gels containing iron oxide particles. The diameter and the number density of the columns were changed by magnetic fields applied while gelation. The column diameter increased with the magnetic field, and the number density of columns decreased with the field. The Young’s modulus of the gels synthesized at higher magnetic fields than 0.5 T was approximately 2 MPa, which was higher than the gel at 0.05 T. In addition, the change in Young’s modulus for the gel synthesized at 0.5 T was 0.19 MPa upon magnetization, which is 8 times larger than that at 0.05 T. The results revealed that the gels with thick columns demonstrate high Young’s modulus and remarkable magnetorheological effect.

**Key words:** gels, magnetic gel, modulus, rheology, magnetorheology

1. **INTRODUCTION**

Magnetorheological softmaterials have attracted considerable attention because of its potential use in field-sensitive actuators and dampers [1]. We have investigated various magnetorheological softmaterials and found that a natural polymer gel containing ferromagnetic particles exhibited negative and significant changes in dynamic Young’s modulus upon magnetization [2]. For example, carrageenan magnetic gel containing barium ferrite with a volume fraction of 0.39 demonstrated reductions in storage Young’s modulus of ~10$^7$ Pa and in loss modulus of ~10$^6$ Pa by applying magnetic field of 1 T. The giant reduction in the modulus is caused by the permanent destruction of a particle network [3]. The absolute change in the modulus was strongly affected by the particle network; that is, the modulus change depends on a type of magnetic particle or matrix [4-6]. In this paper, the magnetic effect on the diameter or the number density of magnetic-particle columns was investigated using microscope observation and dynamic viscoelastic measurements. The magnetic particle is Fe$_2$O$_3$ with a shape of needle, and the matrix is carrageenan. The needle-shaped particle is easy to align in parallel with the magnetic field. We synthesized the magnetic gel in which the magnetic particles were aligned, and measured the dynamic Young’s moduli of the gel before and after magnetization at 1 T.

2. **EXPERIMENTAL PROCEDURES**

2.1 **Synthesis of Magnetic Gel**

Magnetic gels, which consist of needle-shaped particles of Fe$_2$O$_3$ and carrageenan of a natural polymer, have been synthesized. The magnetic particle was anisotropic shape with 320 in length and 40 nm in thickness. A pre-gel solution of the magnetic gel was prepared by mixing the 3 wt.% carrageenan (Wako Chemicals) aqueous solution and the Fe$_2$O$_3$ particles (Titan kogyo) at 90 ºC. The weight ratio of Fe$_2$O$_3$ to that of carrageenan $c_{Fe}$ was 10 wt.%.

The pre-gel solution was poured in a grass mold and was put into magnetic fields for 20 minutes to align magnetic particles, and was cooled to 20 ºC. Magnetic field strengths for alignment were 0.05, 0.5, and 1 T. To find the magnetorheological effect, a strong magnetic field of 1 T was applied to the gel in perpendicular to the particle alignment.

2.2 **Rheological Measurements**

Dynamic viscoelastic measurements were carried out using a Dve Rheospector (Dve-V4, Rheology Co., Ltd). Oscillatory compressional shear was applied to magnetic gels and the stress response was measured; hence elastic modulus obtained stands for Young’s modulus. The frequency was constant at 1 Hz, and the oscillation amplitude was varied from 1×10$^{-5}$ to 9×10$^{-3}$. The offset strain with respect to the sample thickness was kept as 3%. The temperature was maintained at 20.0 ± 1.0 ºC during the viscoelastic measurement. The shape of samples for the mechanical measurement was cubic with dimensions of approximately 10×10×10 mm. Each modulus was determined from an average of two measurements.

2.3 **Microscope Observations**

Microscope observations for the particle columns in carrageenan gels were carried out using an upright microscope (Axio Imager M1m, Carl Zeiss, Inc.) without using cover glass. The film-shaped gel with approximately 3 mm in thick was observed using transmission illumination.

3. **RESULTS AND DISCUSSIONS**

Fig. 1 shows photographs of the particle columns in carrageenan gel which were taken in perpendicular (left)
and parallel (right) to the particle alignment. These photographs indicate that magnetic particles make a columnar structure in the gels. The diameter and number density of the column were measured from the right photograph using image analysis.

Fig. 2 shows the Young’s modulus of the gel before magnetization and the number density of columns, as a function of magnetic fields when particles align. The Young’s moduli of the gel synthesized at 0.5 and 1 T were higher than that at 0.05 T. On the other hand, the number density of the columns decreased with the magnetic field.

Fig. 3(a) shows the distribution of the maximum column diameter for the gels synthesized at various magnetic field strengths. At low magnetic field, the ratio of thin columns was higher than thick columns. However, the ratio of thick columns increased at high magnetic fields. The results of Figs. 2 and 3(a) strongly suggest that the gels with thicker columns bring high Young’s modulus although the number density of the columns was less.

Fig. 3(b) shows the change in Young’s modulus due to magnetization as a function of magnetic fields when particle alignment. The modulus change at 0.5 T was more than 8 times higher than that at 0.05T. This indicates that gels with thick columns exhibited significant magnetorheological effect.

4. CONCLUSION

The magnetic effect on the diameter or the number density of magnetic-particle columns has been investigated using viscoelastic measurements. The column diameter increased with the magnetic field, and the number density of columns decreased with the field. The change in Young’s modulus for the gel synthesized at 0.5 T was 0.19 MPa upon magnetization, which is 9 times larger than that at 0.05 T. The results revealed that the gels with thick columns demonstrate high Young’s modulus and remarkable magnetorheological effect. The obtained results would be useful for designing and fabricating variable elastic materials driven by magnetic fields.

Acknowledgements

This research is partially supported by SUZUKI foundation.

References