Theoretical Explanation of Anisotropic Elastic Modulus of Magnetic Gel

T. Taniguchi, T. Mitsumata, M. Sugimoto and K. Koyama

Department of Polymer Science and Engineering, Yamagata University,
4-3-16, Yonezawa, Yamagata, 992-8510, Japan
Phone: +81-238-26-3056 Facsimile: +81-238-26-3411 e-mail: taniguch@yz.yamagata-u.ac.jp

Recently, it has been reported that a gel with a magnetization has an anisotropic longitudinal elastic modulus\(^1\). In such a magnetic gel, magnetic particles with a typical diameter \(10\mu\text{m}\) are homogenously distributed. In addition, by applying an external magnetic field to this material, magnetic dipole moments of particles are aligned to the same direction with the external magnetic field and can be maintained for a long time. It is considered that these particles cannot be diffused and rotated, since they are completely fixed by the surrounding polymer network. In the experiment done by Mitsumata et al.\(^1\) (see Fig.1), it is found that the longitudinal elastic modulus of a magnetic gel increases and decreases with increasing the density of magnetic moment density for the following two cases: the direction strain is (a) perpendicular and (b) parallel to that of magnetization, respectively. The aim of this study is to explain theoretically the relation between the anisotropy of effective elastic modulus of magnetic gel and the angle between the direction of magnetization and that of the imposed strain. Now we consider a gel where magnetic particles are homogeneously distributed. All the magnetic particles have the same permanent magnetic dipole moment. It is assume that these magnetic particles cannot diffuse and rotate in the gel due to surrounding polymers. The total energy of the magnetic gel consists of the elastic energy and the energy coming from the dipole-dipole interaction. In order to evaluate the effective elastic modulus of the magnetic gel, we consider an infinitesimal deformation of it. In the experiment\(^1\), since the effective elastic modulus is evaluated from sound velocities within the magnetic gel by imposing ultrasonic waves, the characteristic time of deformation of the gel is considerably shorter than that of diffusion of solvent. This means that the total volume of gel is maintained during the deformation. Hence we apply an infinitesimal affine deformation. Since magnetic particles are completely fixed at material points in gel, if the gel is deformed by an externally imposed force, each of particles is moved along with the material points of it. After some calculations using a perturbative method, the increase of the total energy after the deformation can be written up to the second order in an infinitesimal strain, and we can obtain an expression for the effective elastic modulus. In Fig. 2, we show the effective elastic modulus \(\Delta G\) as a function of magnetic moment density of the gel for the following two cases whose directions of magnetization are (a) perpendicular and (b) parallel to the strain direction. In the perpendicular case (a), the elastic modulus increases with magnetic dipole moment density, whereas in the parallel case (b), the modulus decreases. The qualitative behaviors of these two cases are in good agreement with the previous experimental result\(^1\).

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References:
Effect of Magnetization on Storage Modulus of Magnetic Gels

Tetsu MITSUMATA, Akiyasu NAGATA, Takashi TANIGUCHI, and Kiyohito KOYAMA
Department of Polymer Science and Engineering, Faculty of Engineering, Yamagata University, 992-8510 Japan

The Study of Magnetic Gels

Water
Crosslinker
Polymer network
Magnetic Particle

G* = G' + iG''
\( \gamma = 4 \sim 10 \ \mu m \)
\( f = 10 \ Hz \)
\( T = 295 \ K \) (air atmosphere)

Synthesis and Magnetization of Magnetic Gels

Present Study
5wt% κ-carrageenan
Mixed with ferrite

Change in Storage Modulus at 20Hz

Dynamic Viscoelastic Measurement

CONCLUSION

The storage modulus of magnetized magnetic gel was lower than that without magnetization when the ferrite concentration was more than 25 wt.%.