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A Basic Study on the Application of Hydrogel Membrane to a Sensor for Measuring Large Strain

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We experimentally investigated the mechanical and electrical characteristics of the poly vinyl alcohol(PVA) hydrogel which have attracted special interest as a mechanochemical material, and the applicability of the hydrogel membrane to a sensor for measuring large strain. As a result, the PVA hydrogel could be regarded as a Hookean elastic material and was treated as an electric resistance which was proportional to the tensile strain within a linearly elastic range.

INTRODUCTION

Recently polymer gels have attracted special interest as mechanochemical materials and are expected to be applied to artificial muscles. In the field of polymer chemistry, the gels have been known to shrink and swell, and moreover generate stress by changing their surroundings,for instance,pH,ionic strength,electric field and exposing light. However we can find few reseaches in the mechanical and electrical characteristics of the polymer gel except the investigation of the mechanical characteristics of silicone gel by A.Yamada and T.Katabari[1] who applied the silicone gel to the spring mass system. We have almost no studies which try to apply the polymer gel to sensors either.

We pay attention to the poly vinyl alcohol(PVA) hydrogel membrane[2] as a kind of non ionic gel,which can easily be prepared from PVA aqueous solution by repetition of freezing and thawing and has both high elasticity and high water content.

The purpose of this paper is to investigate experimentally the mechanical characteristics and the electrical characteristics of the PVA hydrogel,and is to apply the PVA hydrogel membrane to a sensor for large strain measurement.

As a result, the PVA hydrogel membrane could be regarded as a Hookean elastic material within a range of about 25 %(a true strain= 0.22) in a static tensile test. The gain of displacement for dynamic tensile force decreased rapidly to -40 dB and the phase delayed to 90 degree at the range 10-100 Hz. The PVA hydrogel given sinusoidal impressed voltages to the tensile direction was treated as an electric resistance. The impedance of the PVA hydrogel was hardly influenced by the frequency of the impressed voltage and the value of the resistance was in proportion to the tensile strain within a linearly elastic range. A proportional constant of the PVA hydrogel was 2.0.

This study showed a possibility that the PVA hydrogel membrane can be applied to a sensor for measuring large strain in a low frequency range.

EXPERIMENTAL

The PVA hydrogel membrane used in this experiment was prepared as follows:the PVA aqueous solution, which PVA content(Degree of polymerization=1700) was 10 wt%, was cast on a petri dish and repetitively frozen and thawed six times;membrane thickness was adjusted by controlling the amount of casting solution;one freezing cycle comprised of freezing at -20°C for 23 hours and successive thawing at room temperature for one hour. Fig.1 shows a PVA hydrogel membrane.

We investigate the relationship between a stress and a strain,stress

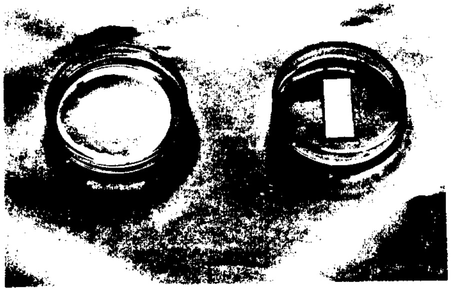


Fig.1 PVA hydrogel membrane.

relaxation and the electrical characteristics of the PVA hydrogel membrane in a static tensile test. A static experimental apparatus is shown in Fig.2 and a scheme of measuring system for static experiment is shown in Fig.3. A sample of PVA hydrogel membrane ⑥ is mounted on the upper and the lower chuck made of CFRP used as electrodes. Because if the chucks are made of metal, metallic ion liquate out to the PVA hydrogel when the electric current flows into the hydrogel. A tensile displacement is given to the sample by rotating a handle ①. The value of the tensile displacement is got by reading of a dial gauge ②. The deflection of the load cell(±0.04mm) is neglected. The tensile load which is applied to the sample is measured with a load cell ③. The output of the load cell is amplified with a D.C. amplifier ⑦ and is read of a voltmeter.

Poisson's ratio can be obtained by measuring the area of the sample with both a camera and an area analyzer. At the same time, the electrical characteristics of the PVA hydrogel is investigated. The voltage drop of the resistor connected with the sample in series, which is impressed by sinusoidal voltages, is amplified by a D.C. amplifier and the output is read of a voltmeter. Thus the current through the sample and its electrical resistance are obtained.Since the PVA hydrogel has high water content,a sinusoidal impressed voltage is used in order to prevent water in the hydrogel from electrolyzing. The static expreiment is carried out with a pulling speed of 0.5-0.7 mm/s at room temperature(20 °C-21.4 °C) keeping the surface of the sample wet.

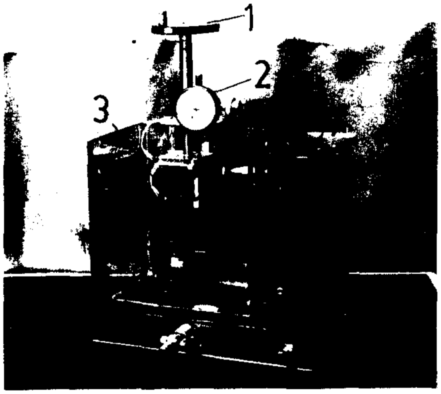
Fig.4 shows a scheme of measuring system for dynamic experiment. The load cell is fitted to a height gauge and can be adjusted its level. The sample is attached just like hanging on to the load cell.The periodical load of an electromagnet to which the output of a frequency oscillator amplified with a power amplifier is supplied acts on a magnet attached to the lower chuck of the sample. The dynamic tensile force given to the sample is measured with the load cell. That output of the load cell is amplified by a wide band amplifier and recorded on a memory recorder. The dynamic displacement of the lower chuck corresponding to the strain in the tensile direction of the sample is measured with a non-contact electro-optical displacement measuring system.

RESULTS AND DISCUSSION

As very extensible materials like polymer gels were tested,we defined a true strain[3] as:

$$\varepsilon_t=\int_{L_0}^{L}\frac{dL}{L}=\ln\frac{L}{L_0}=\ln(1+\varepsilon)$$

where L was the actual length, L_0 was the original length of the hydrogel and $\varepsilon=(L-L_0)/L_0$ was strain. A stress was



1.Handle for moving load cell vertically
2.Dial gauge
3.Load cell
4.Upper chuck
5.lower chuck
6.Sample
7.D.C. amp.

Fig.2 Static experimental apparatus.

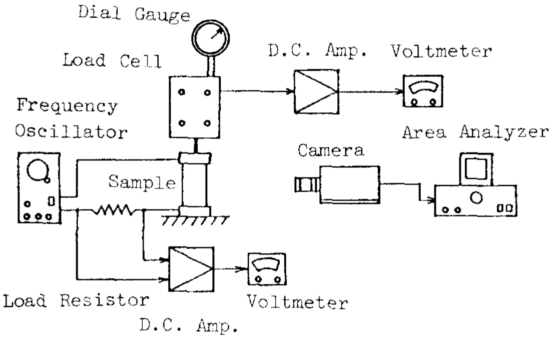


Fig.3 A scheme of measuring system for static experiment.

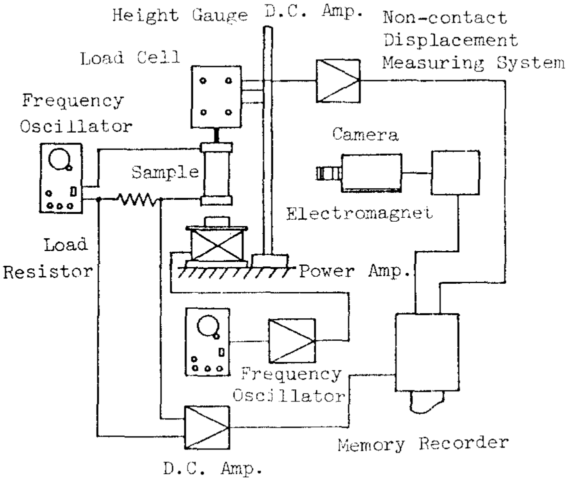


Fig.4 A scheme of measuring system for dynamic experiment.

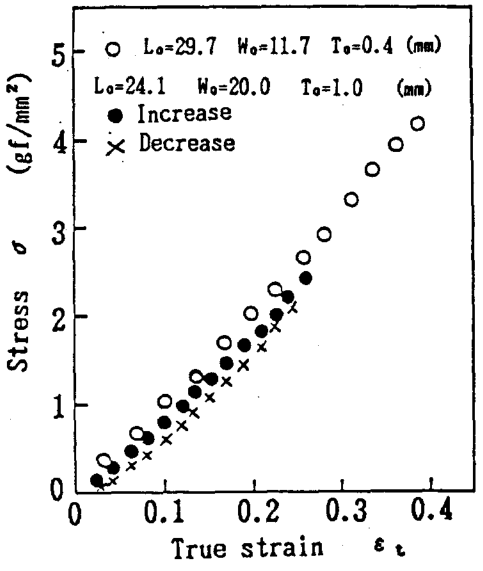


Fig.5 Tensile properties of PVA hydrogel.

defined as:

$$\sigma = \frac{F}{A_0}$$

where F was a tensile force and A_0 was the original area of the hydrogel. A sample of tensile properties of the PVA hydrogel was shown in Fig.5. The stress-strain relations had the linearity determined from Hook's law within a range about ε_t =0.22. This showed results approximately similar to those of other samples with their different dimensions. When the strain exceeded the range, hysteresis was shown. Increasing process for the strain was indicated with symbol● and decresing one was with symbol × . Whole stress for the increasing process was a little higher than that for the decreasing one and the residual strain was about 4 %. The PVA hydrogel membrane could be regarded as a Hookean elastic material within a range of about 25% strain(ε_t=0.22). The volume of the sample was confirmed to be constant in spite of increasing the strain from the result of the area measurement of the sample with the area analyzer. Thus Poisson's ratio of the PVA hydrogel was found to be 0.5. The elastic modulus of the PVA hydrogel was in the range 3 - 50 gf/mm . It is considered that the scattering of the elastic modulus depended on uneven quality on the preparation of the PVA hydrogel. Fig.6 showed stress relaxation data of the PVA hydrogel at various constant strains. As the strain increased, stress relaxation took place. And the stress at each strains became to be constant within a few seconds. It is known that Maxwell model or Voigt model presented by joining elastic and viscous elements are generally applied to polymer gels[4]. However we didn't have a simple model which could apply the PVA hydrogel from the experimental result of stress

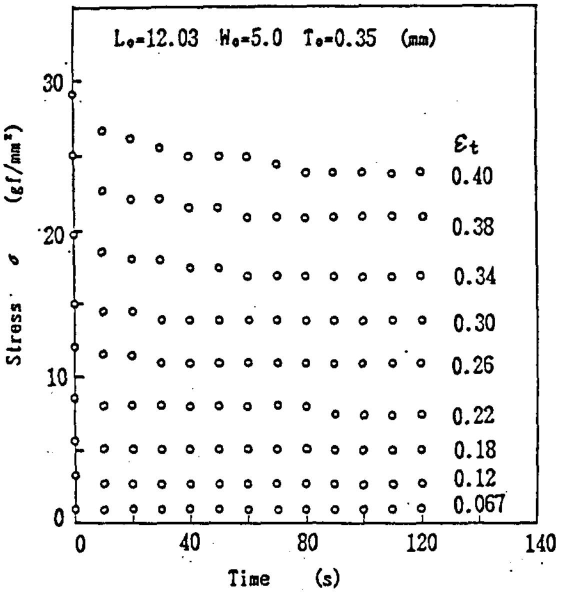


Fig.6 Stress relaxation data of PVA hydrogel at various constant strains.

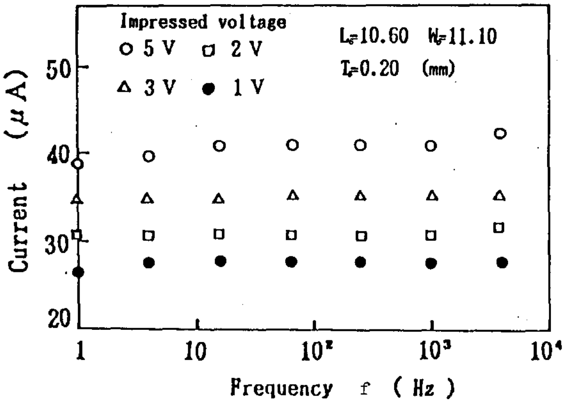


Fig.7 Variation of current with frequency of sinusoidal impressed voltage.

relaxation. Fig.7 showed variation of current with frequency of sinusoidal impressed voltage. Current at each impressed voltage was independent of the impressed frequency and was almost constant. Fig.8 showed variation of current with impressed voltage for extended PVA hydrogel at constant strain. As the impressed voltage increased, current linearly increased. Fig.9 showed variation of electric resistance with true strain for the PVA hydrogel. As the strain increased, the electric resistance increased linearly in the range of which the stress-strain relations had the linearity shown in Fig.5.

Thus the impedance of the PVA hydrogel was independent of the frequency of the impressed voltage. The relationship between the electrical resistance and the tensile strain was

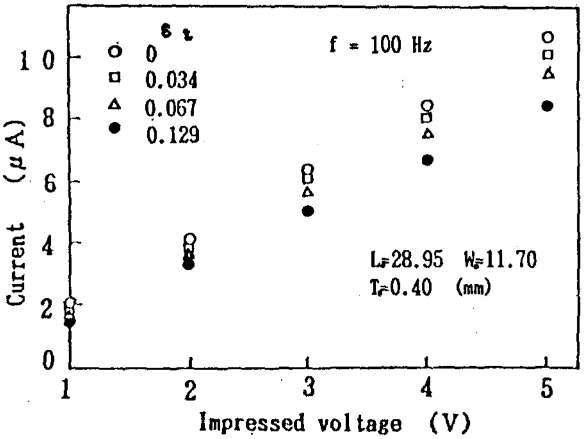


Fig.8 Variation of current with impressed voltage for extended PVA hydrogel at constant strain.

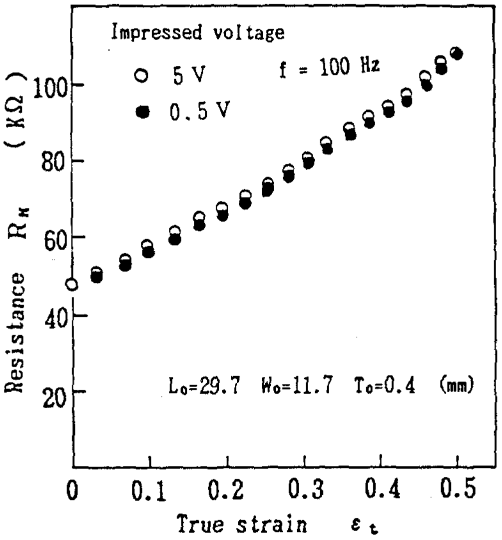


Fig.9 Variation of electric resistance with true strain for PVA hydrogel.

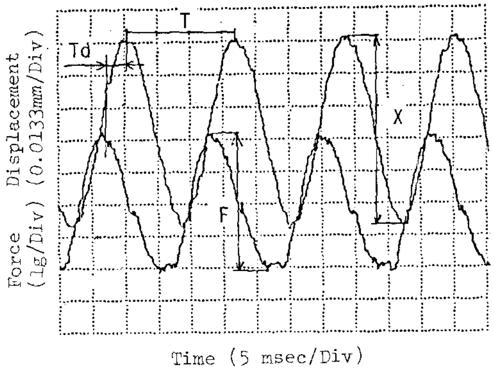


Fig.10 Wave forms of dynamic both displacement and load for PVA hydrogel.(f_a= 60 Hz)

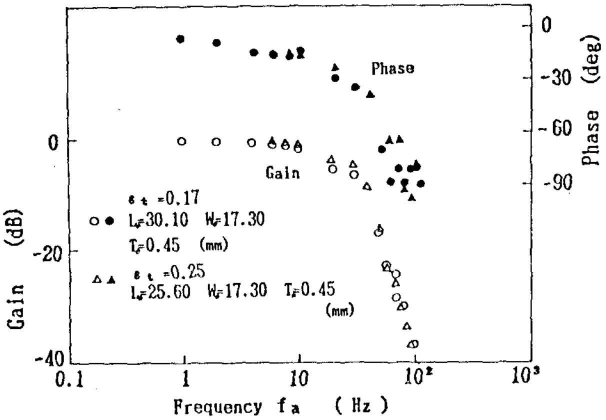


Fig.11 Bode diagram for PVA hydrogel.

indicated as:

$$\frac{dR_H}{R_{H0}} = \alpha \frac{dL}{L_0}$$

where R_{H0} was the initial resistance of the hydrogel at $\varepsilon_t=0$, dR_{H0} was variable of the resistance and α was a constant which depended on the preparation of the PVA hydrogel. A proportional constant of the PVA hydrogel was α = 0.2.

Fig.10 showed a sample of wave forms for dynamic both displacement and load for the PVA hydrogel. Displacement X for dynamic tensile force F, the period of oscillation T and the delay time T could be read off the graph shown in Fig.10. Gain $|G(j\omega)|$ of the frequency response was obtained from the following equation:

$$|G(j\omega)| = 20 \log(\frac{X}{F})$$

Phase ϕ was obtained as:

$$\phi = 360 \frac{T_d}{T}$$

So Bode diagram for the PVA hydrogel could be plotted as shown in Fig.11. However we expressed the gain at the exciting frquency f_a = 1 Hz as 0 dB in this graph. The gain decreased rapidly and the phase delayed as the exciting frequency increased over 10 Hz. The gain decreased to -40 dB and the phase delay was 90 degree at 100 Hz. It was found that the frequency response of the PVA hydrogel differ from that of rubber and silicone gel. Fig.12 showed a sample of wave forms of both current for the sinusoidal impressed voltage and dynamic displacement. The frequency of the sinusoidal impressed voltage was necessary to be made enough high compared with the exciting frequency. The both phase of the dynamic diplacement and the current agreed precisely. Thus it was found that the change of the current corresponds not to that of the stress but to that of the strain.

CONCLUSIONS

We experimentally studied on the mechanical and electrical characteristics of the PVA hydrogel and the applicability of the PVA hydrogel membrane to a sensor. The summary of the results was:

1.The PVA hydrogel membrane could be regaded as a Hookean elastic material within a range of about 25% strain in a static tensile test.

2.Stress relaxation of the PVA hydrogel showed that the stress at various strains became to be constant within a few seconds.

3.The gain of displacement for dynamic tensile force decreased rapidly and the phase delayed as the exciting frequency increased over 10 Hz. The gain decreased to -40 dB and the phase delay was 90 degree at 100 Hz.

4.The PVA hydrogel given sinusoidal impressed voltages to the tensile direction was treated as an electric resistance which was independent of the impressed frequency and proportional to the tensile strain. A proportional constant of the PVA hydrogel was 2.0.

It was shown that the PVA hydrogel membrane could be applied to a sensor for measuring large strain in a low frequency range.

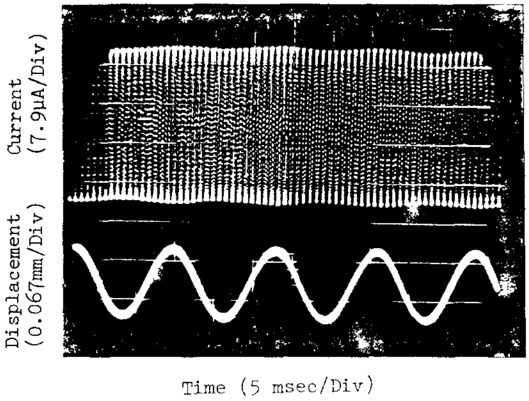


Fig.12 Wave forms of both current for sinusoidal impressed voltage and dynamic displacement. (L_0= 19.7, W_0= 17.3, T_0= 0.45, ε_t =0.195, impressed voltage 5 V, f=1 kHz, exciting frequency f_a= 60 Hz)

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