Water-Induced Plasticization of Solution Cross-Linked Hydrogel Networks: Energetics and Mechanism[†]

G. V. N. Rathna, D. V. Mohan Rao, and
P. R. Chatterji*

Division of Organic Coatings & Polymers, Indian Institute of Chemical Technology, Hyderabad, 500 007 India

Received January 4, 1994
Revised Manuscript Received September 14, 1994

Hydrogels are cross-linked networks of hydrophilic polymers with an exceptional capacity for water uptake.[1] The driving force for swelling, the swelling pressure, π, ensues from the difference in the chemical potential of the solvent, within and without the gel.

The kinetics of swelling could also be treated from the sorption point of view. However, the contours of the time versus penetrant uptake curve more often than not deviate from the classical Fickian mode. In these cases, the sorption process is not a passive diffusion of the solvent molecules into the void spaces of the network but includes a concomitant relaxation of the network segments by the advancing solvent front, which results in the plasticization of the material with a large increase in volume.

The fundamental equation[2,3]

$$Q_t/Q_\infty = kt^n \tag{1}$$

where Q_t is the amount of solvent uptake at time t, Q_∞ the equilibrium value, and k a constant characteristic of the system, has been used to distinguish three types of sorption behavior, with the value of n as the monitoring index.[2,4] For a perfect Fickian process, where the rate of penetration of the solvent is slower and hence the rate-determining step, in comparison to the chain relaxation rate, the value of n is close to 0.5. When the mobility of the penetrant is very much faster than the chain relaxation rate, then the solvent uptake is directly proportional to the time and this is called case II sorption. When the rates of penetrant mobility and segmental relaxation are comparable, the value of n ranges between 0.5 and 1.0, and these are classified as the anomalous cases.

However, the swelling characteristics of a network are also influenced by the conditions under which the network has been formed. de Boer et al.[5] have reported that solution cross-linked polyethylenes could swell to higher limits than bulk cross-linked samples. This was interpreted as follows: when cross-linked in solution, the macromolecular chains may assume more probable extended conformations, and during drying the chains are crumbled and squeezed into a very small volume space. The natural tendency of the chains will be to attain maximum relaxation, or, in other words, the dried gel will have a self-driving force to swell.[6,7]

We have been investigating the physicochemical properties of solution cross-linked hydrogels with a view to develop bioerodible matrices for controlled-release applications.[8–10] We were particularly interested in the system of glutaraldehyde cross-linked gelatin (Gelx) containing small amounts of entrapped (carboxymethyl)cellulose (CMC; as the sodium salt) chains. While gelatin provided a physically strong and chemically versatile network, the extent of swelling of the system could be beautifully controlled by adjusting the amount of CMC.[10] More significantly, the systems prepared as solution cross-linked networks could go through several cycles of swelling and drying. Hence, it was necessary to get a comprehensive picture of the water-induced glassy to rubbery transition of these hydrogels, so that the release characteristics from a glassy gel may be better understood.

The preparation of the gels and the methods of monitoring swelling have been described in detail elsewhere.[10] An aqueous solution of a gelatin and CMC mixture was prepared at 100 °C. This was poured between rectangular glass slabs separated by a Teflon gasket (0.5 cm thick) and allowed to gel. Later the gelled slab was carefully dislodged and cut into circular disks with a cork borer (1.6-cm diameter). The disks were treated with a 1% glutaraldehyde solution for cross-linking. Amino acid analysis of the glutaraldehyde-treated gelatin samples confirmed the total involvement of lysine residues in the cross-linking. The blocks were then allowed to dry at room temperature for several days until they attained a constant weight. The diameter and thickness of the circular disks were of 1.6 and 0.5 cm in an "as is made" state and 0.8 and 0.3 cm after drying, respectively. The swelling studies were carried out in triplicate in doubly distilled water. The samples were kept in a thermostated water bath of required temperatures in the range of 25–60 °C with an interval of 5 °C. The swellings were monitored gravimetrically every 15 min for the first hour, every 30 min for the next 8 h, and thereafter every 24 h until they attained equilibrium (≈7 days).

Figure 1 depicts a typical swelling curve for the Gelx–CMC system. The main figure tells the percentage solvent uptake as a function of time at constant temperature. The sorption data for the penetration of the solvent into the network have been fitted into the following relation:

$$\log(Q_t/Q_\infty) = \log k + n \log t \tag{2}$$

Q_t and Q_∞ represent the percentage swelling at time t and at equilibrium, respectively. The slope of the above plot, n, indicates the type of transport mechanism (Figure 1, inset).

Our discussions are confined to the events taking place during the initial 6 h. During this phase the dry and collapsed network is struggling to fan out under the influence of the penetrating water molecules. In Figure 2 the values of n for the different compositions studied are plotted as a function of temperature. The deviations are too small to be of statistical significance. Hence, it can be logically concluded that n is invariant with temperature and composition. Both numerical calculations and graphical estimations yield a value of 0.7 for n.

This means a change from anomalous to Fickian mode with an increase in temperature, as has been suggested by several investigators,[3,11] is not happening in this system. Subsequent differential scanning calorimetric experiments provided the explanation. Glutaraldehyde cross-linked gelatin gels did not register a T_g, in their thermograms. This is perfectly understandable because gelatin being a protein gets decomposed on heating before it can soften or melt.[12] Also thermolabile H bonds are not the main structural elements of this network.

---

* To whom correspondence should be addressed.

[†] IICT Communication No. 3342.

0024-9297/94/2227-7920$04.50/0

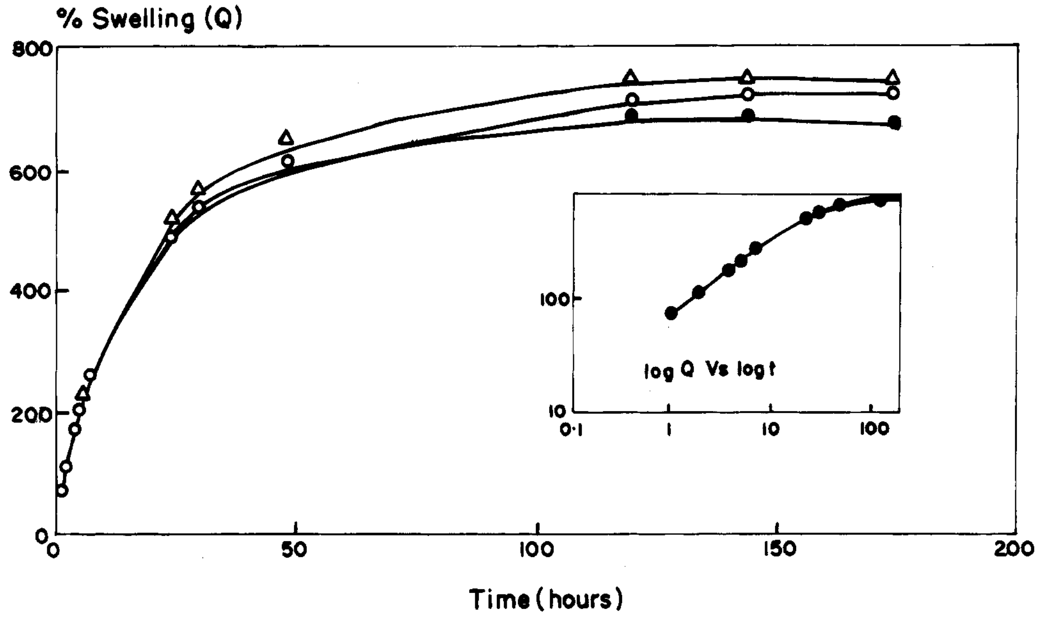

Figure 1. Dynamic equilibrium swelling of Gelx–CMC gels (1:0.1, w/w) at 35 °C in water (in triplicate: ●, ○, △).

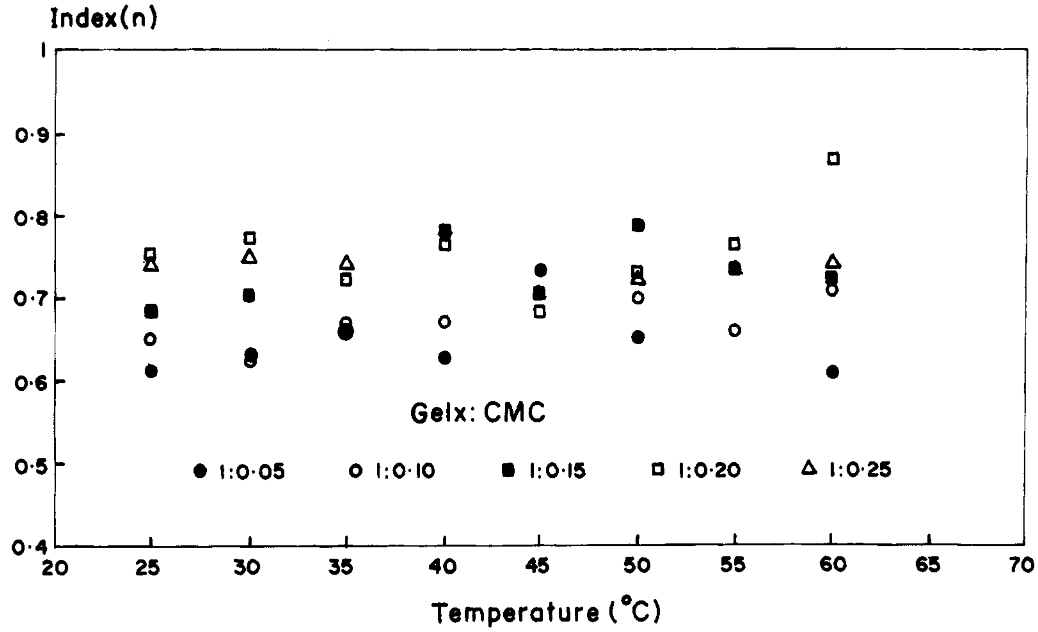

Figure 2. Variation of Index(n) as a function of temperature and composition.

Instead, strong inter- and intrachain covalent cross-links formed by the bifunctional aldehyde with the ϵ amino groups of the lysine residues hold the network together.[13,14] Hence, a temperature-induced anomalous to Fickian transition is not warranted at all.

The Flory–Rehner[15] model treats the volume change that accompanies the swelling of a cross-linked polymer network in terms of at least three separate yet inter-related processes in operation.

$$\pi_{\text{swelling}} = \pi_{\text{mixing}} + \pi_{\text{elast.}} + \pi_{\text{ionic}} \qquad (3)$$

Several theoretical models have been proposed for the swelling of hydrogels which separately calculate the mixing contributions based on the lattice theory, the elastic contributions from the affine and phantom network theory, and the ionic contributions from the ideal Donnan theory.[16–20] Conceptually, the terms on the right-hand side of the equation cumulatively stand for the solvent-induced plasticization of the network, which is essentially the kinetically envisaged penetrant diffusion/chain relaxation process.

The initial rates of swelling (first 6 h) at different temperatures were calculated from dynamic swelling curves as described by Vyavahare et al.[21] We calculated the activation energies for this initial phase. This phase essentially reflects the entry of water molecules into the glassy network and the resultant unfolding of the crumbled segments into a more relaxed state. We have not attempted to itemize the individual contributions of the processes involved because this would have necessitated a large number of disputable assumptions for the thirsty networks.[22,23]

There are several reports in the literature[3,24–28] regarding the activation energies for the diffusion and permeation of solvent molecules into polymer films or networks. These are in the range of 15–20 kcal/mol. However, it should be noted here that these values stand for the passive diffusion and permeation of solvent molecules through the polymer networks which do not

Table 1. Activation Energies for the Swelling of Gelx–CMC Gels

composition of Gelx–CMC	activation energy (kcal/mol)	composition of Gelx–CMC	activation energy (kcal/mol)
1:0.05	51.12	1:0.20	56.63
1:0.1.0	65.16	1:0.25	69.89
1:0.15	59.27		

undergo any dimensional change. In comparison, the energies listed in Table 1 are for the entire process of solvent entry, stretching of the network segments, and consequent large-scale macroscopic dimensional change of the sample. From the mechanistic point of view, the value of "*n*" indicates that the process is anomalous, where the rates of solvent penetration and chain relaxation are on comparable time scales.

References and Notes

(1) Wichterle, O. *Encyclopedia of Polymer Science & Technology*; Mark, H. F., Gaylord, N. G., Bikales, N. M., Eds.; Interscience: New York, 1971; Vol. 15, p 273.

(2) Windle, A. H. *Polymer Permeability*; Comyn, J., Ed.; Elsevier Applied Science: London, 1983; Chapter III, p 75.

(3) Hargoppad, S. B.; Aminabhavi, T. M. *Macromolecules* **1991**, *24*, 2598.

(4) Lucht, L. M.; Peppas, N. A. *J. Appl. Polym. Sci.* **1987**, *33*, 1557.

(5) de Boer, P.; Pennwss, A. J. *J. Polym. Phys.* **1987**, *14*, 187.

(6) Poh, B. T.; Adachi, K.; Kotaka, T. *Macromolecules* **1987**, *20*, 2563.

(7) Poh, B. T.; Adachi, K.; Kotaka, T. *Macromolecules* **1987**, *20*, 2569.

(8) Chatterji, P. R.; Kaur, H. *Polymer* **1992**, *33*, 2388.

(9) Kaur, H.; Chatterji, P. R. *Macromolecules* **1990**, *23*, 4868.

(10) Chatterji, P. R. *Macromolecules* **1991**, *24*, 4214.

(11) Hopfenberg, H. B.; Frisch, H. C. *J. Polym. Sci., Polym. Phys.* **1965**, *7*, 405.

(12) Chatterji, P. R. *J. Appl. Polym. Sci.* **1989**, *37*, 2203.

(13) Richards, F. M.; Knowles, J. R. *J. Mol. Biol.* **1968**, *37*, 231.

(14) Quiocho, F. M.; Richards, F. M. *Proc. Natl. Acad. Sci. U.S.A.* **1964**, *52*, 833.

(15) Flory, P. J. *Principles of Polymer Chemistry*; Cornell University Press: Ithaca, NY, 1953; Chapter VIII, p 577.

(16) Hooper, H. H.; Baker, J. P.; Blanch, H. W.; Prausnitz, J. M. *Macromolecules* **1990**, *23*, 1096.

(17) Peters, A.; Candau, S. J. *Macromolecules* **1986**, *19*, 1952.

(18) Daoud, M.; Bouchaud, E.; Jannink, G. *Macromolecules* **1986**, *19*, 1955.

(19) Prange, M. M.; Hooper, H. H.; Prausnitz, J. M. *AIChE J.* **1989**, *35*, 803.

(20) Wu, I. C.; Peppas, N. A. *J. Appl. Polym. Sci.* **1993**, *49*, 1845.

(21) Vyavahare, N. R.; Kulkarni, M. G.; Mashelkar, R. A. *J. Membr. Sci.* **1990**, *49*, 207.

(22) Peppas, N. A.; Gurny, R.; Doelker, E.; Buri, P. *J. Membr. Sci.* **1980**, *7*, 241.

(23) Jerabek, K.; Shea, K. J.; Sasaki, D. Y.; Stoddard, G. J. *J. Polym. Sci., Polym. Chem.* **1992**, *30*, 605.

(24) Hargoppad, S. B.; Aminabhavi, T. M.; Ballundgi, R. H. *J. Appl. Polym. Sci.* **1991**, *42*, 1297.

(25) Saleem, M.; Asfour, F. A.; Kee, D. D. *J. Appl. Polym. Sci.* **1989**, *37*, 617.

(26) Morris, E. L.; McCrum, N. G. *J. Polym. Sci.* **1963**, *1*, 393.

(27) Winkler, D. A.; Starks, A. *J. Appl. Polym. Sci.* **1988**, *35*, 51.

(28) Smith, P. M.; Fisher, M. M. *Polymer* **1984**, *25*, 84.