Interaction of poly(ethylene oxide) with solvents: 4. Interaction of water with poly(ethylene oxide) crosslinked hydrogels

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The nature of the association of water with poly(ethylene oxide) has been studied using crosslinked gels containing 78.4 to 92.5% by weight of poly(ethylene oxide). The interaction of the hydrogel with water is generally attributed to hydrogen bonding between the hydrogen of the water molecule and the ether oxygen of the network. The ether oxygen atom takes on one molecule of water to form a monohydrate and then complexes a further two molecules of water to form a stable trihydrate. Evidence for the formation of these hydrates has been obtained by measuring the heat of partial swelling, the specific heat of hydration and the crystalline melting endotherms. Differential scanning calorimetry showed that trihydrate formation depends quantitatively upon the weight fraction of poly(ethylene oxide) in the gel. A helix model for the stable trihydrate is tentatively proposed.

(Keywords: hydrogel; poly(ethylene oxide); water; hydrates; heat of partial swelling; differential scanning calorimetry; helix model)

INTRODUCTION

In our earlier publications[1–3], we have shown that hydrogels prepared from poly(ethylene glycol) (PEG) can be partially crystalline and are capable of imbibing large quantities of water, depending upon the composition, the crosslink density and the molecular weight of PEG. The presence of water in linear PEG has been the subject of much discussion, and various techniques have been employed to investigate the binding of water with it, for example n.m.r. and i.r.[4,5], calorimetry[2,6–9], Raman spectroscopy[10,11] and light microscopy[12,13]. These studies indicate that a high degree of orientation of water molecules with respect to the polymer chain must exist, as a result of which in aqueous solution PEG molecules form a hydrogen-bonded complex in which three water molecules are associated with each repeat unit. Evidence of a 1:1 complex has also been reported[2,4,14]. One of these hydrates appears to be a distinct species, which survives considerable aqueous dilution. Although the state of water in cellulose acetate[15–17], polyacrylamide[18,19] poly(vinyl alcohol)[18,19], poly(hydroxyethyl methacrylate)[20], polysaccharide and xanthan gums[18,19], agarose and crosslinked dextran gels[21] has been studied, we have not found any significant report in the literature on water in crosslinked hydrogels made from poly(ethylene glycol), though they are mentioned briefly in reviews by Ratner[22] and Roorda[23].

Crosslinked poly(ethylene oxide) hydrogels were synthesized in these laboratories for the formulation of controlled-release dosage forms of drugs[24–28]. A knowledge of the nature of interaction of these hydrogels with water assists in such design. Differential scanning calorimetry, simple calorimetry and mechanical analysis have been used in this present study to elucidate any such interactions, and are reported in this paper.

EXPERIMENTAL

The polymer network system used comprises a series of block copoly(ether–urethanes) based on methylenebis(4-phenylisocyanate) and poly(ethylene oxide) with 1,2,6-hexanetriol as crosslinking agent. Synthesis of the network has been described in our earlier publication[3]. The following naming system is used for various elements in a given polymer.

The first number with suffix M represents the ratio of the number of moles of triol to PEG and the second number PEG-6000 represents the commercial code for the PEG (of our measured $M_n = 8310$). Thus, 1M-PEG-6000 is the hydrogel based on poly(ethylene glycol) 6000, methylenebis(4-phenylisocyanate) and crosslinked with 1 mol (equivalent to the actually measured M_n of PEG-6000) of 1,2,6-hexanetriol. All studies unless otherwise stated were carried out on 1M-PEG-6000. The term poly(ethylene glycol) (PEG) is used for the oligomeric starting materials containing terminal hydroxyls, while poly(ethylene oxide) is used when the hydroxyls have been reacted and the unit is an integral part of the polymer network.

Calorimetry

For simple calorimetric measurements, a Dewar vacuum flask was used at ambient temperature, 50 and 70°C. In order to calibrate the apparatus, 150 ml of water was heated in the Dewar flask by means of an electric coil with a low output. The flask was gradually heated

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for 3 min and the temperature rise was followed to calculate the heat capacity of the calorimeter, which was found to be 108.75 J. The heat of swelling of the films in water was determined both for entirely dry samples and for the samples preswollen to known values. The preswelling was done by sealing the films, spread on a wire gauge, over water in a jar and letting them stand for a day or more depending on how much water of swelling was desired. In each case, a sample corresponding to 6 g of the dry polymer was placed into a polythene bag, which was suspended inside the calorimeter over 150 ml of water but isolated from the vapour. It was left to stand for 24 h to attain thermal equilibrium, then the bag was ruptured and the polymer allowed to mix with the water. The increase in the temperature, caused by swelling to the maximum limit of the gel, was measured and the heat of partial swelling per gram of dry polymer calculated.

Calorimetry at elevated temperature was repeated as above in a constant-temperature bath at 50 and 70°C respectively. It was observed that, during the 4 min timescale in which the swelling was done, the heat loss due to the insulation was not appreciable. The maximum temperature drift was found to be only 0.04°C. Three identical samples were swollen and average values were recorded.

Differential scanning calorimetry

A Du Pont model 910 differential scanning calorimeter, coupled with a 990 thermal analyser, was employed for all the melting measurements. Some 5–20 mg of the dry or swollen gel was transferred to an aluminium pan (normally used for liquids). The pan was then hermetically sealed to prevent the loss of water, cooled to $-80°C$ with liquid nitrogen, then heated at a rate of $10°C\,min^{-1}$ up to 50°C. The d.s.c. cell was constantly purged with dry nitrogen gas to avoid moisture contamination during subambient temperature operation. As can be seen from *Figures 6, 7* and *8*, overlapping peaks are obtained for swollen hydrogels. The baseline was constructed from the onset of the first peak to completion of the second peak and the heat of fusion was calculated from the area under the melting peak with a planimeter. Where crystalline melting points are quoted, these refer to the minimum of the endotherm peak. The specific heat determination[29,30] was carried out on the Perkin–Elmer DSC-1 by using a reference standard of sapphire disc over the temperature range 15–25°C at $8°C\,min^{-1}$. The values presented in *Figure 4* are the average values for three identical determinations on each sample.

Indentation tests

For the indentation test, a thin block of polymer was prepared in a Teflon-lined mould. The block of polymer, of dry weight 15.45 g and dimensions $2.1 \times 1.5 \times 0.9\,cm^3$, was swollen in water to about 40 pph of its dry weight. It was then left on a wire gauze placed over water in a desiccator to swell uniformly in an atmosphere of water vapour. This took approximately 9 days, when the whole block had become a transparent rubber. The swelling at this time was 66.3% of the dry weight (1.6 mol of water uptake per ether oxygen). It was then left in the open air to lose some of the imbibed water. When the swelling fell to 55.6% of the dry weight (i.e. 1.34 mol of water uptake per ether group), the transparent appearance had not changed. The first indentation was then made. It was observed that the loss in weight of the swollen gel at the end of each run never exceeded 1%. At the end of the runs the block was removed and left to stand in a beaker of water. After 30 min, it was removed, wiped dry and put back into the desiccator containing water. When it had equilibriated for 5 h it was reweighed and the second indentation was made. Again, the gel was put back into a beaker of water. This cycle of swelling, equilibration and indentation was repeated several times to obtain readings at different degrees of swelling for the block of polymer. An Instron tensile tester model TM-M was used. The machine was, however, adapted for this particular test by the inclusion of the assembly shown in *Figure 1*. One half of the light aluminium frame is hung on by means of a metal hook to the base of the cell, where the upper crosshead of the Instron would normally hang. The triangular base of this part of the frame is the platform on which the xerogel being indented is placed. The other half of the framework, the rectangular frame carrying the indentor, is mounted within and held by the flat plate grips of the lower crosshead. The indenting sphere, which is cemented onto a vertical rod is suspended vertically above the triangular platform and within the vertical rod of the frame. In the operation, the plate that holds the gel remains stationary, hanging from the tester cell, while the framework that carries the indentor in contact with the gel moves vertically. The tester cell was adjusted to give a full-scale deflection of 200 g. The probe (indentor) was of radius 4.785 mm and was run at a crosshead speed of $0.05\,cm\,min^{-1}$ and a chart speed of $5\,cm\,min^{-1}$. Theoretical considerations of the procedure of indentation are based on the method described by Waters[31], which requires that indentation needs to be sufficiently small to justify the assumption that the free boundaries are stress-free and further the rubber is isotropic and elastic. In our study we have adjusted the experimental conditions to match the case where a rigid ball pressed into a semi-infinite elastic medium is simulated and can be described by the following equation[31]:

$$d = \frac{KP^{2/3}}{(3G)^{2/3} r^{1/3}} \tag{1}$$

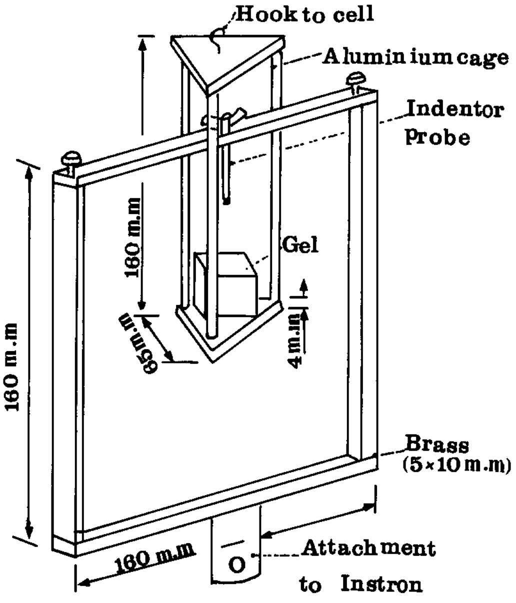

Figure 1 Adaptation to the Instron for indentation tests

where d = indentation, G = modulus of elasticity, r = radius of probe, P = force of indenting probe and K = constant, which depends on the moduli of the rigid ball and Poisson's ratio for the material.

The force P of the indenting probe and the indentation d were read from the chart paper, knowing the full-scale deflection and the speed of the indenting probe. The respective corresponding points were fed into a mean straight-line program in a table calculator. From the gradient of the best straight line so obtained, G was calculated employing equation (1). Using the different values of G obtained, plots of modulus against the corresponding moles of water incorporated in xerogels were constructed.

Tensile testing

The dry gel was studied using an Instron tensile tester model TM-M equipped with a constant-temperature box. Dumbbell sections of the gel were cut from the film samples using a standard gauge cutter. The thickness of each specimen was measured at three different locations using a micrometer screw gauge. The average of such values was taken as the thickness of the sample. Tensile data were obtained at various temperatures and each sample was conditioned *in situ* in the constant-temperature box for 1 h before testing was performed. The runs were made at a uniform speed of 0.05 cm min^{-1} for both the crosshead and the chart using a full-scale load of 20 kg. The tangents were drawn at the origin to the respective chart plots of stress against strain[32] obtained at different temperature. The initial modulus was derived as the slope of the respective tangents so drawn, divided by the corresponding initial cross-sectional area of the elastomer. The G values plotted in *Figure 5* are the averages obtained from triplicate samples at the respective temperatures.

RESULTS AND DISCUSSION

The nature of water in various hydrogels, namely cellulose acetate[15–17], polyacrylamide[18,19], poly(hydroxyethyl methacrylate)[20], polysaccharides and xanthan gums[18,19], agarose and crosslinked dextran gels[21], has been examined using different techniques. The three types of water below[20,23,33] are usually considered to be present:

(i) bound water—this water is thought to be closely associated with polar groups of the polymer, through hydrogen bonding;

(ii) interfacial water—this type of water is possibly associated with the hydrophobic part of the polymer; and

(iii) free or bulk water—this water behaves like normal water.

It has also been reported[19,34,35] that the total enthalpies (heats of fusion) by d.s.c. on various hydrogel–water systems (based on hydrophilic monomers other than PEG) do not show an equivalence between the area under the melting endotherms and total amount of water added in the system. The observed difference has been commonly referred to as non-freezing water. This non-freezing water is not readily characterizable in these poly(ethylene oxide) hydrogels as they are quite highly crystalline in the dry state and this crystallinity is first destroyed by the addition of water than replaced by low-melting crystallites, which we take to be a trihydrate melting in the vicinity of −16°C. The free water shows as a second peak. The association between water and poly(ethylene oxide) is quite strongly exothermic and an estimate of 'non-freezing' water content would require a more detailed analysis of all of these factors than given herein. It will thus not be discussed in detail.

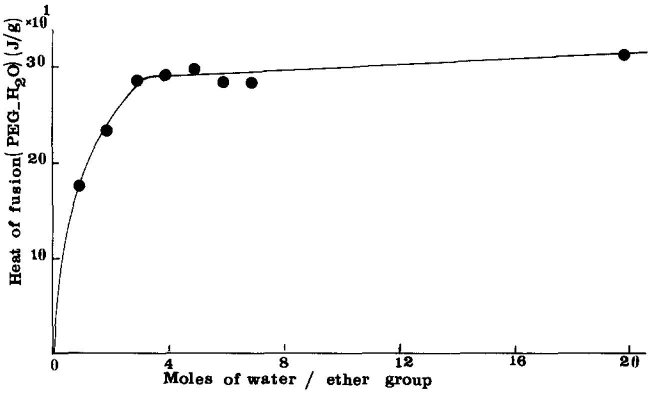

Figure 2 Total heat of fusion of PEG–H$_2$O hydrates vs. moles of water/ether group for PEG 5700

In order to gain insight into the interaction of hydrogels based on PEG with water, we have studied the heats of fusion, as measured by d.s.c., of a simpler linear purchased poly(ethylene glycol) of quoted $\bar{M}_n$ = 5700. *Figure 2* displays the heat of fusion plotted against moles of added water per ether group. The heat of fusion per gram plotted here is derived from the analysis of the area under all of the peaks melting from −40°C to approximately +5°C and normalized to 1 g of added water. The heat of fusion increases from 176 J g^{-1} at a ratio of molecules of water:ether oxygens of unity to 284 J g^{-1} at a ratio of 3. This increased but little to 307 J g^{-1} at ratios as high as 20. The freezing of pure water was measured as a control and our measured value of 334.1 J g^{-1} compares very well with the reported value[35] of 334.0 J g^{-1}. These observations and *Figure 2* indicate that beyond approximately 3 mol of water per ether group the state of association of water with PEG changes. The second form of water is revealed by a second endothermic peak in the d.s.c. trace.

A significant contribution to the loss in enthalpy of fusion up to 3 mol H$_2$O per ether group is due to melting of the PEG crystallites and also partly due to the microchain 'dissolution' process. This explanation gains further support from the results of a separate experiment on hydrogels where a positive heat of partial swelling was observed up to the addition of 1.3 mol H$_2$O per ether group (*Figure 3*). These findings are consistent with the results of other workers[6,7], who have reported a positive value for heat of solution of PEG (M_n = 6000), which varied from 20.56 to 25.16 J g^{-1} of polymer containing 0.0299 g (0.001 mol per ether group) to 0.4003 g (1 mol per ether group) of water in the system. Moreover, the following equation would also predict that the value of total enthalpy change on the melting of PEO crystallites in contact with water, ΔH_f, would be less than heat of fusion ΔH_f° according to the following equation:

$$\Delta H_f = \Delta H_f^\circ - \Delta H_{soln}^\circ \qquad (2)$$

The conformational changes of PEG chains that occur on dissolution make a significant contribution to the overall process, which can be regarded as composed of the following steps[6]. The sum of these provide the overall

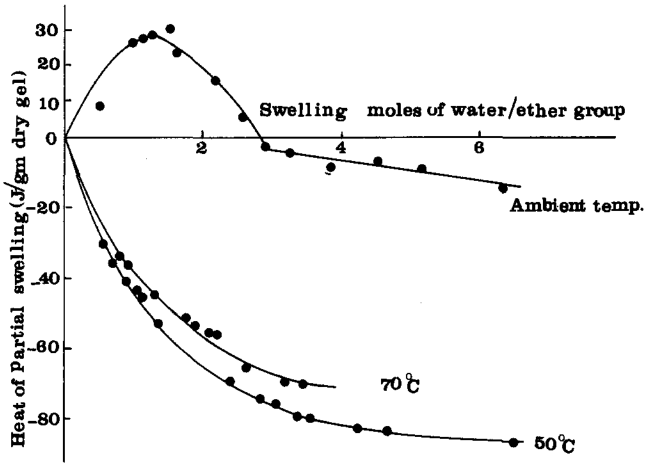

Figure 3 Heat of partial swelling for poly(ethylene oxide) hydrogel in water at different temperatures

solution process, namely:

$$
\begin{array}{lll}
\text{PEG(s, helical)} & & \\
\quad = \text{PEG(l, non-helical)} & \Delta H_{\mathrm{f}}^{\circ} & \\
\text{PEG(l, non-helical)} + H_2O\text{(l)} & & \\
\quad = \text{PEG(solution, non-helical)} & \Delta H_{\mathrm{m}} & (3) \\
\text{PEG(solution, non-helical)} & & \\
\quad = \text{PEG(solution, helical)} & \Delta H_{\mathrm{h}} & \\
\text{PEG(s)} + H_2O & & \\
\quad = \text{PEG(solution, helical)} & \Delta H_{\mathrm{m}} &
\end{array}
$$

Maron and Filisko[6] have determined a value for $\Delta H_{\mathrm{m}} = -164.54\,\mathrm{J\,g^{-1}}$ of polymer. This means that on formation of a helix from the random coils in aqueous solution, $164.54\,\mathrm{J\,g^{-1}}$ are liberated; conversely, this quantity is required to disrupt the helix. These conformational changes indicate that the nature of water interaction with PEG is quite different from that in hydrophilic polymers based on monomers other than PEG. The formation of specific hydrates in the PEG–water system is becoming accepted[1,2,4,6–12,23,36] and interfacial water[20,23], does not seem to play any significant role, as it is generally accepted that iceberg formation[33,36–39] (also referred to as interfacial water) around the $-CH_2-CH_2-O-$ chain is somewhat suppressed by the hydrogen-bond formation between ether oxygen atom and water molecules. Thus in the present investigation, the nature of water in PEO gels is discussed below in terms of bound water (specific hydration) and free water only.

Conventional simple calorimetry was carried out for the crosslinked hydrogel (1M-PEG-6000) to determine the heat of partial swelling. The results are shown in *Figure 3*. The heat of partial swelling from the dry state to any point on the plot was determined by subtracting the heat of partial swelling (of the initially partly swollen gel) to its maximum equilibrium swelling from the heat of complete swelling of the dry gel at the same temperature.

The plot (*Figure 3*) for the ambient swelling shows an endothermic process indicated by the rise in heat of partial swelling, which attains a maximum around 1.3 mol of water per ether group. Beyond this point the endotherm reduces until the process finally becomes exothermic at 2.8 mol of water. The striking change in slope at 2.9 mol H_2O per ether group is a clear indication of changing nature of water association with the polymer, which we regard to be the completion of formation of a trihydrate. The initial rise in partial heat of swelling is associated with the absorption of heat to melt the crystallites. To confirm this, the crystallites were first melted before swelling by preheating the gel slightly above the melting points of the crystallites (50°C). The partial heat of swelling at 50 and 70°C is plotted as a function of moles of water per ether group and is shown in *Figure 3*. Although the three plots shown (*Figure 3*) at different temperatures are not strictly comparable, because they have different degrees of complete swelling and the difference used to determine each point is against a different total water content of complete swelling of each plot, it can be seen from the curve that for the swelling at elevated temperature no endothermicity is caused in the absence of crystallites.

The specific heat per gram at constant pressure (c_p) was determined for dry 1M-PEG-6000 gel, relative to the sapphire disc and for portions of the gel equilibrated with varying known quantities of water at a narrow temperature range of 15–25°C on the differential scanning calorimeter, which is an extension of the basic function of the calorimeter[30]. By taking the c_p of the water-swollen gel based on moles of water per ether group from the sum of the appropriate proportions of the c_p(dry gel) and c_p(water), the c_p change attributed to the association between water and the polymer was determined. When plotted against the molar ratio of H_2O:ether group, minima were obtained close to values of 1, 3 and 6 of

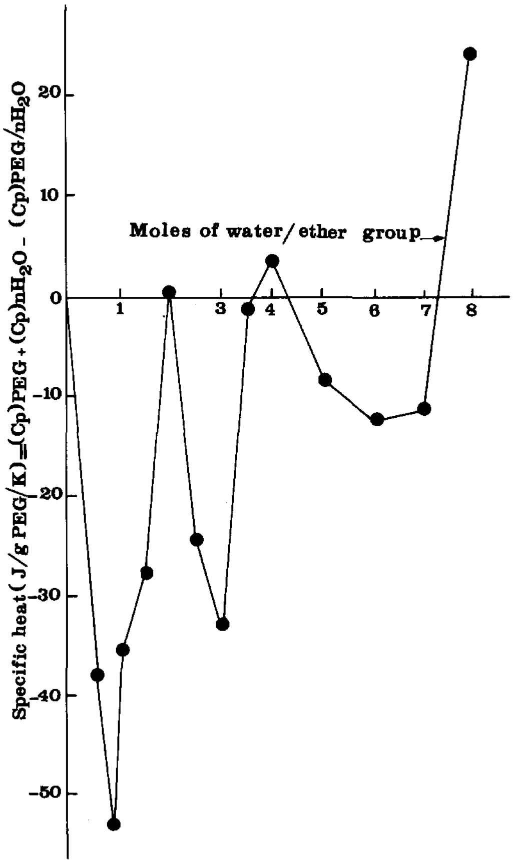

Figure 4 Specific heat of hydration of poly(ethylene oxide) hydrogel in water

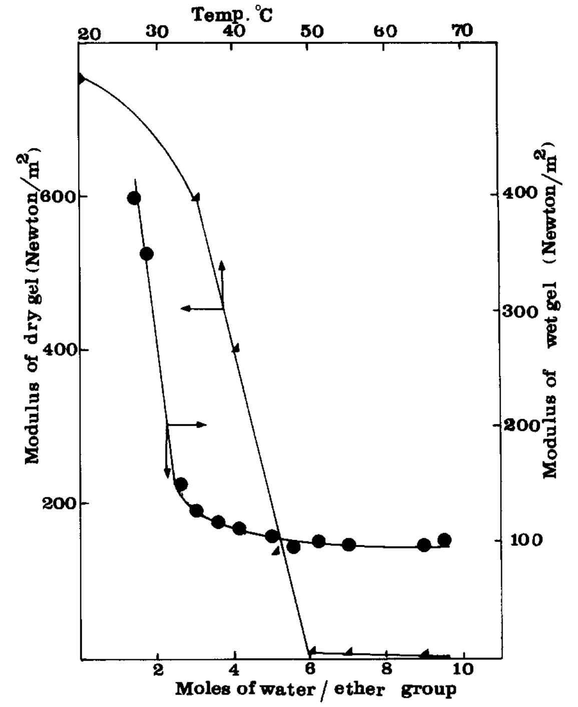

Figure 5 Modulus of poly(ethylene oxide) hydrogel vs. water incorporated and temperature: (●) wet polymer (1M-PEG-6000); (▲) dry polymer (1M-PEG-6000)

this ratio (*Figure 4*). The minimum at a ratio of 1 coincides approximately with the disappearance of crystallinity and the correspondence to a molar ratio of unity is possibly a coincidence and not indicative of a complex. The minimum at a ratio of 3 is most probably related to the formation of a trihydrate complex. It is tempting to interpret the minimum at a ratio of 6 as associated with a hexahydrate, but as we have no other evidence for such a complex, we do not wish to do more than note the possibility. If the poly(ethylene oxide) is converted almost completely to a trihydrate with three molecules per ether group of water then, and only then, one would expect significant breaks in the plot of physical properties against water content at a ratio of H_2O:$-CH_2CH_2O-$ of approximately 3:1.

Mechanical tests were carried out on water-swollen hydrogel in order to monitor the changing pattern of the modulus with the disappearance of crystallites as water was imbibed. This is in some ways analogous to the stretching of the dry samples at different temperatures. The modulus of the gel containing varying amounts of H_2O per ether group was studied by the indentation method. *Figure 5* shows a rapid fall of the modulus during the incorporation of the first two moles of water, during which the crystallites are broken as water is taken into the gel. It is clear that there is a change in slope of the plot in the region of 2.8 mol of water, after which the value of G changes only slightly as more water is absorbed. This result implies that at 3 mol of water per $-CH_2CH_2O-$ unit, a change in the nature of the water association occurs. The shear modulus of elasticity of the dry gel, as a function of temperature, is also shown in *Figure 5*. The modulus decreases with rise in temperature and drops sharply between 20 and 50°C, indicating the melting of the crystallites[2].

If indeed the hydrogel containing PEO in the polymer chain forms different hydrates, then such species should have melting points that are quite different from those of water or the dry crystalline gel. In order to investigate this phenomenon, d.s.c. experiments were performed on fully swollen as well as on partially swollen hydrogel samples containing varying amounts of water. *Figure 6* shows a typical d.s.c. heating scan of 1.25M-PEG-6000 hydrogel fully swollen in water. Three distinct transitions are discernible. One is in the region of -72 to -65°C, which is in the region of the T_g for the linear PEG–water system[2]. The second transition peak at -10°C is an endotherm, representing melting of a PEO–water hydrate. The third is around 3°C, which is due to the melting of free water in the hydrogel. The endotherm peak around -10°C is of the trihydrate complex and is consistent with our previous finding[2] in the case of linear PEG samples. In order to clarify the phenomenon further, various amounts of water were incorporated in the gel and the quantified d.s.c. curves for 1M-PEG-6000 are reproduced in *Figure 7*. It is obvious from the figure that pure water and dry hydrogel gave endotherms with minima at 3 and 65°C caused by melting of the respective crystals (*Figure 7*, curves 1 and 2). In the measurement of a composition comprising 1 mol of water per ether group of PEO in the polymer chains, a new and characteristic peak of the proposed monohydrate[2] appeared at 16°C, while the melting of the anhydrous PEO spherulites in the gel is depressed to 41°C from 65°C (*Figure 7*, curve 3). At a ratio of 2.9 another new and most characteristic peak believed to be a trihydrate appeared at -10°C while the peaks at 16 and 41°C have disappeared. Further, on the addition of 3.3 mol of water the peak around -10°C becomes broad but still remains as a single peak. Much larger amounts of water result in two distinct endotherms for the trihydrate and melting of free water in the gel. From *Figure 7* (curves 3, 4 and 5) it is clear that monohydrate and trihydrate melting endotherms are preceded by an exothermic peak, which is the cold crystallization[2,14]. The monohydrate tends to convert into a much more stable trihydrate state at a hydration level around 2 mol of water per ether group in the gel. However, the relative stability of the trihydrate seems quite consistent relative to monohydrate, as reported

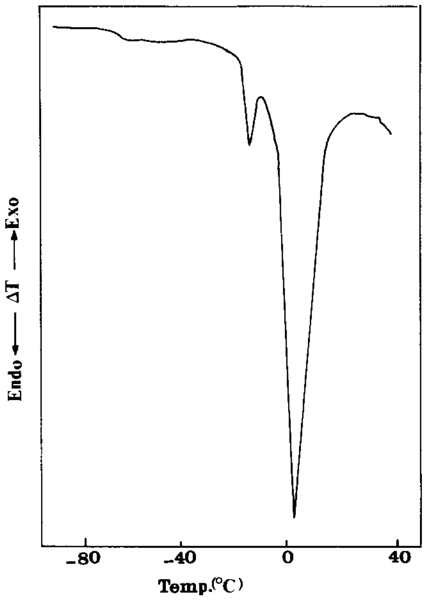

Figure 6 D.s.c. heating scan for fully swollen hydrogel (1.25M-PEG-6000). Scan rate 10°C min⁻¹

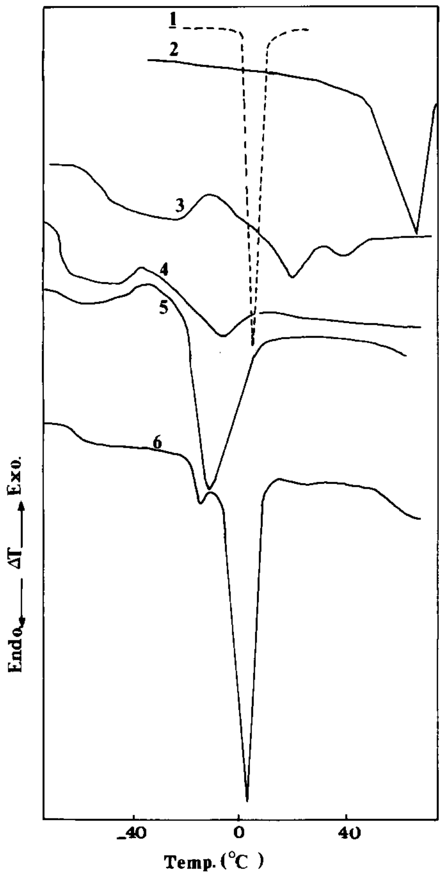

Figure 7 D.s.c. heating scan for hydrogels (1M-PEG-6000) swollen to various amounts of water per ether group. Scan rate 10°C min^{-1}. Curves: (1) pure water; (2) dry gel; (3) 1 mol of water; (4) 2.9 mol of water; (5) 3.3 mol of water; (6) maximum uptake of water

earlier[2]. Furthermore, the effect of crosslinking on the formation of hydrates was examined, and it was found that, beyond 1.75 mol of the crosslinking agent (triol) per mole of PEO in the chain, the monohydrate peak around 16°C was absent. This inhibition of monohydrate formation is reminiscent of its reduction in higher-molecular-weight linear poly(ethylene glycols) as demonstrated earlier[2]. The d.s.c. curves for 1M-PEG-6000 compared with 2M-PEG-6000, 3M-PEG-6000 and 4M-PEG-6000 are displayed in *Figure 8*. Two features are clearly discernible: the increase in crosslink density of the gel results in the reduction of imbibition of free water (melting around 3°C) and the increase in the melting temperature of trihydrate. In order to quantify the formation of trihydrate as a function of PEO in the gel, peak area per weight fraction of PEO in the swollen gels is plotted against weight fraction of PEO in the dry gel (*Figure 9*). It is obvious from the figure that trihydrate complex formation is largely independent of the amount of crosslinking agent in the gel and the area remains approximately constant over a wide range of PEO contents in the network. This is in stark contrast to the monohydrate formation, which is reduced in quantity or inhibited completely with increasing crosslinking agent. In the dry state, the poly(ethylene oxide) xerogel comprises crystalline and amorphous domains. The relative proportion of these two domains is very dependent on the amount of crosslinker. On addition of water and subsequent formation of trihydrate, there is greater freedom of movement. This apparently enables the previously amorphous poly(ethylene oxide) to be able to form a greater proportion of trihydrate crystalline regions.

All the results have shown that the interaction of the hydrogel with water is enthalpically favoured and this is due to the secondary interaction of hydrogen bonding between the hydrogens of the water molecules and the ether oxygens of the network. The ether oxygen atom in the polymer attaches a molecule of water by a hydrogen-bonding process, then takes on a further two molecules of water per ether group to form a trihydrate complex.

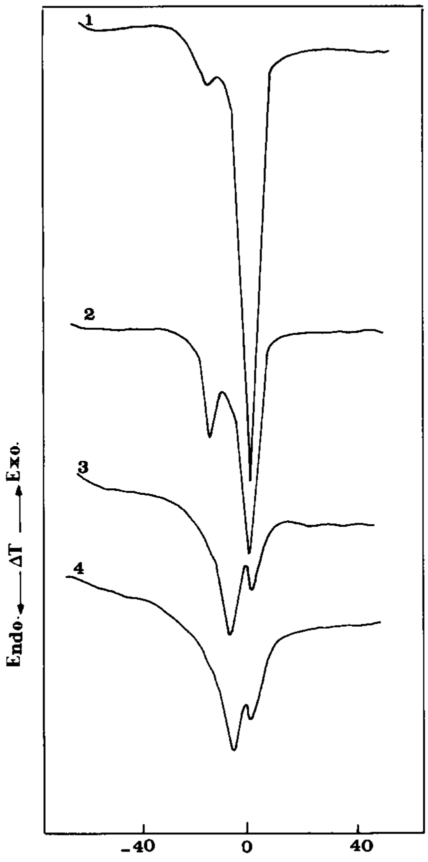

Figure 8 D.s.c. heating scan for fully swollen hydrogels of varying crosslink density: (1) 1M-PEG-6000; (2) 2M-PEG-6000; (3) 3M-PEG-6000; (4) 4M-PEG-6000

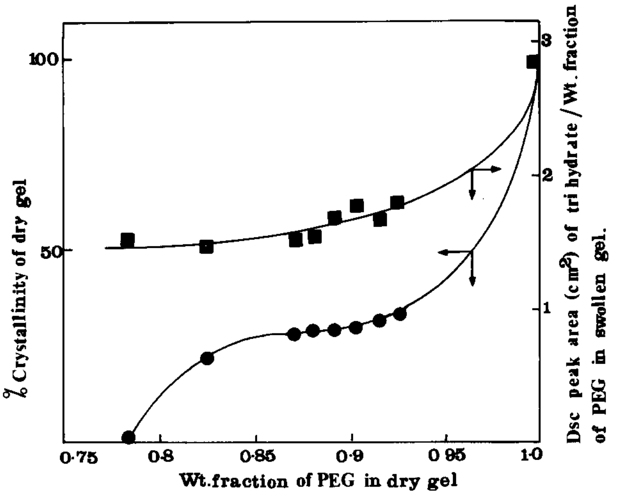

Figure 9 Crystallinity of dry gel and d.s.c. peak areas of trihydrate vs. weight fraction of poly(ethylene oxide) in the dry gels: (■) d.s.c. peak area of trihydrate; (●) crystallinity (%) of dry gel

Simultaneous with the formation of the monohydrate is the breaking down of the residual crystallites in the gel, a process that is responsible for the endothermicity of the reaction (*Figure 2*). The fact that this process proceeds at all implies that the free-energy change on forming the monohydrate is negative. The entropy change on formation of the trihydrate is also known to be negative[1]. The mono- and trihydrates are capable of coexisting in the linear PEG[2] but to date we have not found evidence for this coexistence in crosslinked systems. It has been shown that the trihydrate freezes from −16 to −40°C and is stable in the solution of linear PEG at higher temperatures[2], possibly up to the melting point of pure PEG-6000 (65°C)[8], surviving even in the presence of a large excess of water[2]. The crosslinked polymer at 100°C still swells with approximately 3 mol of water[1]. If water is present in excess of 3 mol per ether group, another complexed form of hydrated water may be observed in the d.s.c. analysis. It has not been possible by our techniques to characterize fully these higher complexes. Hexahydrate formation has been reported[36] and may possibly be substantiated by the minimum at 6 mol of water in *Figure 4*. We remain cautious on drawing any such conclusions on these higher associations from the work presented herein. The existence of a very stable trihydrate seems very conclusive and, based on our own work[2] and the literature reports[7] that the PEG exists as a helix in aqueous solution, a molecular model has been constructed of a postulated plausible structure for the trihydrate complex from water (*Figure 10*). This structure contains a helix repeating every seven ethylene oxide units. It comprises an exterior shell of the $-CH_2CH_2-$ units of the poly(ethylene oxide) with the ether groups turned inwards to a concentric complexed shell of 3 mol of water per ether group. The helix has a channel down the centre large enough to admit small ions into a structure analogous to some peptides and complexing crown ethers. Though this postulated structure fits the evidence as we know it, there could no doubt be alternatives, and further definition will require study by techniques such as low-temperature X-ray diffraction, which we expect to pursue. It is presented as its structure indicates the possibility that poly(ethylene oxide) in water presents a relatively hydrophobic surface to the bulk water and an interior hydrophilic channel that might be utilized for selective inclusion of ions and suitable compounds where poly(ethylene glycols) of molecular weights sufficient to form the trihydrate are present.

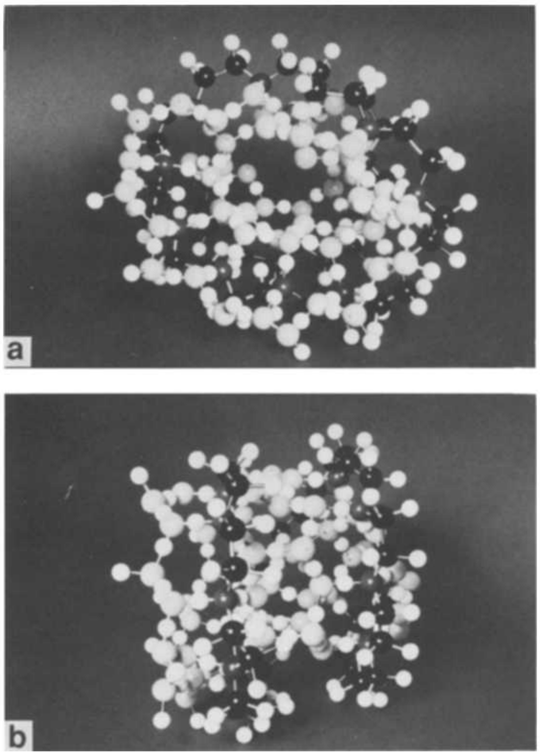

Figure 10 (a) End view and (b) side view of trihydrate complex model

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