Modification of the dynamic swelling behaviour of poly(2-hydroxyethyl methacrylate) hydrogels in water through interpenetrating polymer networks (IPNs)

B. Ramaraj and Ganga Radhakrishnan*
Polymer Division, Central Leather Research Institute, Adyar, Madras-600 020, India
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Interpenetrating hydrogel networks based on poly(vinyl alcohol) (PVA) and 2-hydroxyethyl methacrylate have been synthesized. Water absorption and desorption properties of these hydrogels were analysed extensively. The influence of solutes (urea, potassium iodide, D-glucose, sodium chloride) on equilibrium water content (EWC) of these gels was also studied. Incorporation of PVA into poly(2-hydroxyethyl methacrylate) in the form of an interpenetrating polymer network (IPN) increases the EWC. The existence of different classes of water in this IPN system is shown by water melting curves using differential scanning calorimetry. The morphological features of these films were studied by scanning electron microscopy.

(Keywords: polymer networks; equilibrium water content; morphology of hydrogels)

INTRODUCTION

Hydrogels are a unique type of implant polymers which derive their name from their affinity for water and the incorporation of water into their structures. These gels have a significant role in the field of biomaterials as contact lenses, artificial corneas, soft tissue substitutes, burn dressings, etc.[1-5].

The first hydrogel contact lens from poly(2-hydroxyethyl methacrylate) (PHEMA) was developed by Wichterle and Lim in 1960[6]. Since then a large number of hydrogels have been developed, of which PHEMA[7,8] has been intensively investigated because of its good biocompatibility[9]. However, the use of PHEMA hydrogel is somewhat restricted owing to its insufficiently permeable character and limited water intake[10]. It is therefore necessary to modify PHEMA to increase the water content and influence the transport and interfacial properties[11]. So far this has been done by copolymerizing HEMA with vinyl pyrrolidone[12] or potassium sulfopropyl methacrylate[13] and by grafting with polyvinyl pyrrolidone[14], but the disadvantage of such systems is their structural collapse during extensive swelling, if the systems are not crosslinked.

This prompted the authors to explore the possibility of developing an interpenetrating polymer network (IPN) to counteract such a problem. An IPN is an intimate combination of two polymers, both in the network form, at least one of which is synthesized or crosslinked in the immediate presence of the other[15,16]. Here, we were particularly interested in developing a two-component hydrogel matrix, wherein the degree of swelling can be effectively controlled by varying the composition and crosslinking.

In this work, poly(vinyl alcohol) (PVA) is used to enhance the swelling behaviour of PHEMA. PVA is water soluble and a good film-forming material with emulsifying effect. PVA-based hydrogels are extensively studied because of their resistance to fungi[17], high degree of permeability and anti-thrombogenicity and because they can be used also in the form of sponge as artificial skin or filling material for artificial blood vessels, artificial trachea, chest and subcutaneous tissues[18]. The peculiarity of the PVA gel is that after drying and reswelling it will return to the original state. Such properties are lacking in many other gels such as gelatin and agar-agar. The recent development of soft contact lenses from PVA has been reported by Lee[19,20].

The simplicity of this non-ionic system is that these reactions have been carried out in water medium without any emulsifying agent, thereby satisfying the fundamental requirement for a biomaterial[21].

In the ongoing effort to develop polymer networks[12-24], we report the synthesis of IPNs from PVA and PHEMA. The equilibrium water content (EWC) of these IPNs was investigated extensively in view of the great importance of such properties for biocompatibility[9,25] and solute transport[26].

EXPERIMENTAL

Materials

Poly(vinyl alcohol) (M_w 14000, BDH, Germany), glutaraldehyde (25% solution, SDSFinechem, India), butanediol dimethacrylate (Polyscience) and potassium persulfate (BDH, Germany) were used as received. 2-Hydroxyethyl methacrylate was distilled under vacuum before use.

* To whom correspondence should be addressed

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Table 1 Composition of IPN system

Sample code	Percentage composition PVA	HEMA[a]	Crosslinking agent
A-	100	–	2% GLA
IA	50	50	2% GLA
IA_1	50	50	–
IB	53	47	2% GLA
IB_1	53	47	–
IC	56	44	2% GLA
IC_1	56	44	–
ID	59	41	2% GLA
ID_1	59	41	–
IE	62.5	37.5	2% GLA
IE_1	62.5	37.5	–
IF	67	33	2% GLA
IF_1	67	33	–
IIB	47	53	2% GLA
IIB_1	47	53	–
IIC	44	56	2% GLA
IIC_1	44	56	–
IID	41	59	2% GLA
IID_1	41	59	–
IIE	37.5	62.5	2% GLA
IIE_1	37.5	62.5	–
IIF	33	67	2% GLA
IIF_1	33	67	–
G	–	100	BDDMA

GLA, glutaraldehyde
[a] HEMA crosslinked with 2% 1,4-butanediol dimethacrylate (BDDMA)

Preparation of hydrogels

The initial step is the preparation of 5% PVA solution in oxygen-free distilled water at 60°C with continuous stirring in a three-necked flask. Next, calculated quantities of 2-hydroxyethyl methacrylate (HEMA), butanediol dimethacrylate (2 wt% of monomer) and potassium persulfate (3 wt% of monomer) dissolved in distilled water are added simultaneously and stirred at 60°C for 30 min to complete the exothermic reaction. After this the temperature is increased to 90°C and kept at that temperature for about 90 min with continuous stirring. For the preparation of a full IPN, the same procedure is adopted except for the addition of glutaraldehyde (2 wt% of PVA) to crosslink PVA. The different compositions obtained are indicated in *Table 1*.

Swelling studies

Dynamic swelling measurements were made by gravimetry. Hydrogel specimens of identical size (three from each sample) were immersed in excess deionized water for specified periods, then blotted free of surface moisture and weighed. The water absorbed by the hydrogel network is quantitatively represented by the EWC, where:

$$\text{EWC}\ (\%) = \frac{\text{Weight of water in the gel}}{\text{Weight of dry gel}} \times 100$$

The final value of EWC is an average of three determinations. After reaching equilibrium swelling, the hydrogel specimens were exposed at 25°C in a dust-free chamber to allow for water desorption. The desorption was followed by weighing the specimens at various time intervals using a Mettler H33AR single-pan balance accurate within 2%.

Thermal analysis

Differential scanning calorimetry (d.s.c.) measurements were made using a Du Pont 2000 Thermal Analyzer from -30 to $+20$°C at a heating rate of 2°C min^{-1} and from room temperature to 500°C at a heating rate of 10°C min^{-1}.

Scanning electron microscopy

The surface morphology of the full- and semi-IPN films was scanned using a Philips scanning electron microscope. The samples were gold-coated prior to examination.

RESULTS AND DISCUSSION

IPN hydrogels: water-binding properties

A range of hydrogels with PVA and PHEMA were prepared. The polymer chains were crosslinked with the respective crosslinking agents in solution, where the macromolecules assume the most probable extended conformations. As a result, in the dehydrated state, the average end-to-end distance will be shorter and such polymers will have an overwhelming tendency to become solvated. Poh *et al.*[27] describe them as 'high free energy' or 'hungry' networks. The swelling characteristics of such networks were investigated and the results are presented in *Figures 1* and *2*. *Figure 1* gives the effect of compositional variation of PVA on the swelling behaviour of full-IPNs and semi-II-IPNs (HEMA crosslinked). All full IPNs (IA, IIB, IIC, IID, IIE, IIF) and semi-II-IPNs (IA_1, IIB_1, IIC_1, IID_1, IIE_1, IIF_1) show a higher percentage of swelling than the PHEMA individual network (G). *Figure 2* gives the effect of PHEMA compositional variation on swelling behaviour of semi- and full-IPNs and shows an increase of swelling with decrease of PHEMA content and, for the corresponding composition, semi-II-IPN shows higher EWC values than the full-IPN. The effects of composition and crosslinking on EWC are shown in *Figures 3* and *4*. From these figures it is clear that all semi-II-IPNs have higher EWC than full-IPNs, because of the extra crosslinking which prevents the permeation of water molecules into the network. The more hydrophilic nature of PVA compared to PHEMA increases the EWC in all

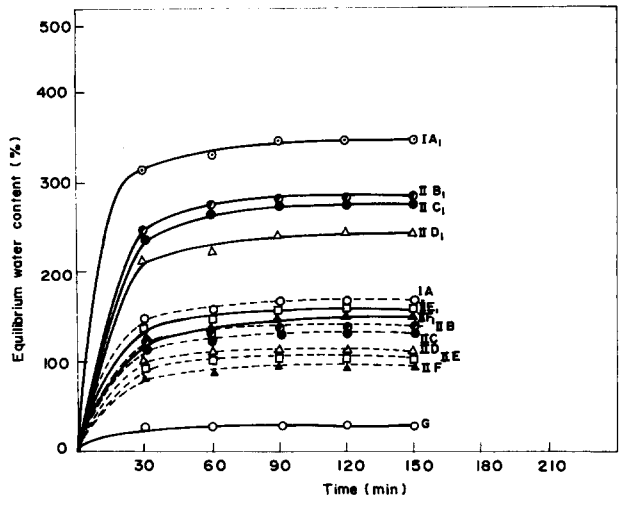

Figure 1 Effect of PVA variation on swelling behaviour of PHEMA/PVA semi-II-IPN and full-IPN

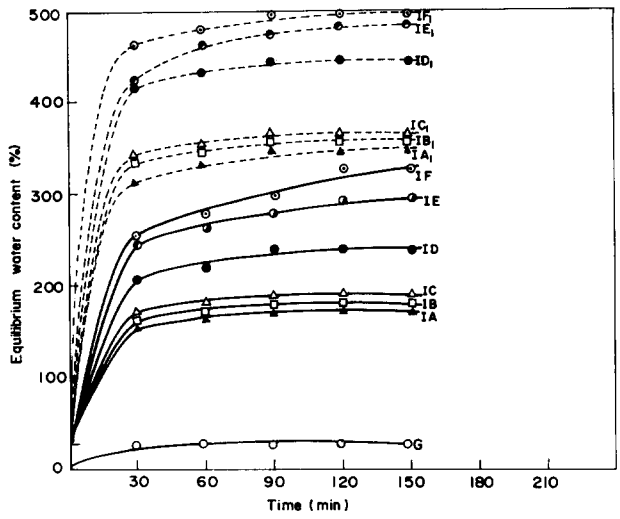

Figure 2 Effect of PHEMA variation on swelling behaviour of PHEMA/PVA semi-II-IPN and full-IPN

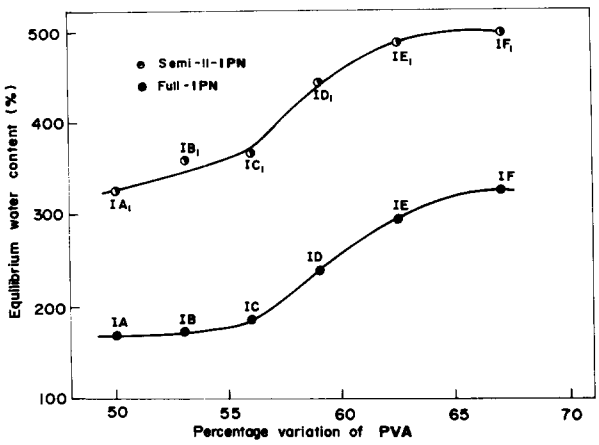

Figure 3 Effect of PVA variation on swelling ratio of semi-II-IPN and full-IPN

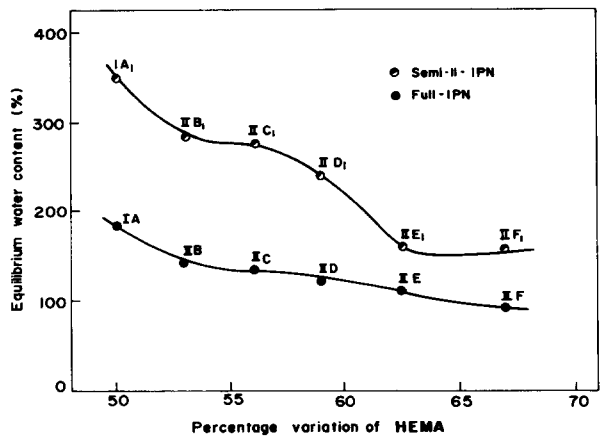

Figure 4 Effect of PHEMA variation on swelling ratio of semi-II-IPN and full-IPN

systems, because of the strong interaction of PVA with water.

IPN hydrogels: water desorption

The use of hydrogels for the controlled release of water-soluble drugs is well known[28,29]. It is therefore reasonable to study the release of water from the polymer network with time, which is presented in *Figures 5–8*. It is clearly seen that the full-IPN takes water more slowly and releases it more quickly than the semi-II-IPNs. If the PVA content is less than the PHEMA content, the rates of release for semi-II-IPNs and full-IPNs are

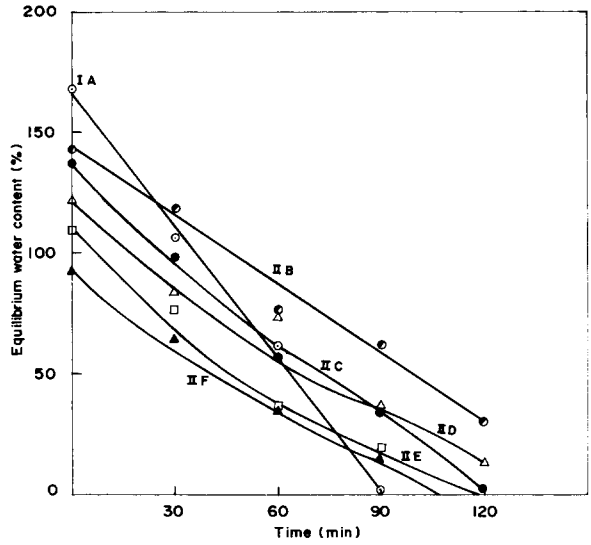

Figure 5 Effect of PVA variation on desorption studies of PHEMA/PVA full-IPN

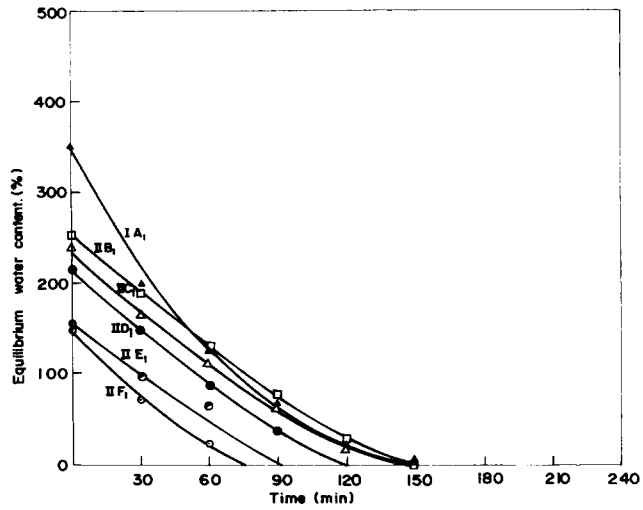

Figure 6 Effect of PVA variation on desorption studies of PHEMA/PVA semi-II-IPN

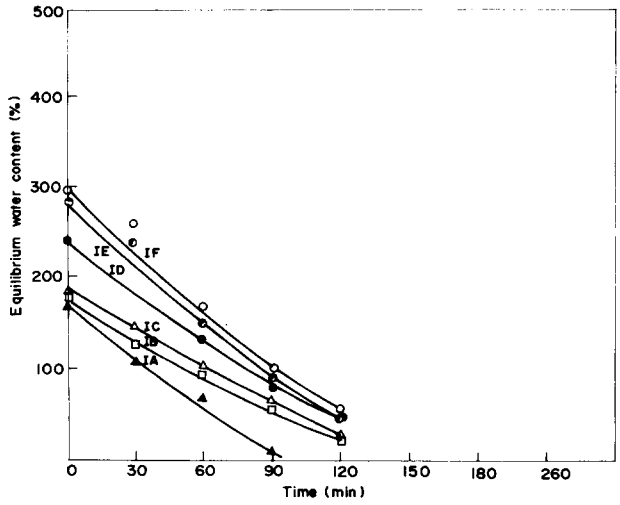

Figure 7 Effect of PHEMA variation on desorption studies of PHEMA/PVA full-IPN

comparable, whereas if the content of PVA is higher than that of PHEMA in the PHEMA/PVA IPN system, the rate of release of water for the semi-II-IPN system is very slow compared to the full-IPN, where the PVA is not crosslinked with glutaraldehyde. This is due to the higher affinity of water for PVA.

Influence of solutes on swelling behaviour

The equilibrium swelling behaviour of a polymer network in a solvent is the result of a balance between osmotic and the restoring elastic pressures. The presence of solutes in the surrounding aqueous medium is capable of tilting this balance[30–32], which may result in either a decrease or an increase in swelling. Solutes such as potassium iodide (KI) and urea show an increase in percentage of swelling over that in pure water (*Table 2*). An increase in swelling was accompanied by absorption of a relatively large amount of solutes which perhaps counteract the polymer–polymer interaction. In particular, urea is capable of breaking hydrogen bonding of the bound water and permeating into the interface region that is considered to exist in the hydrophilic polymer systems[33]. However, solutes such as D-glucose and sodium chloride show a significant decrease in percentage of swelling. This is an interesting phenomenon, which is assumed to be caused by an increase in osmotic pressure of the external medium. The same trend is observed for semi-II-IPNs (IIF_1, IA_1, IF_1), full-IPNs (IIF, IA, IF) and individual networks (A, G), but full-IPNs have a smaller percentage of swelling than the semi-II-IPN. This is due to the extra crosslinking in the full-IPN by glutaraldehyde, which reduces the water intake.

Thermodynamic status of water

From the above data it is clear that the water intake for the full-IPN is greater than for the PHEMA individual network and less than for the semi-II-IPNs, which is well supported by the d.s.c. melting curves of water shown in *Figure 9*. The area under the curve for the full-IPN (IA)

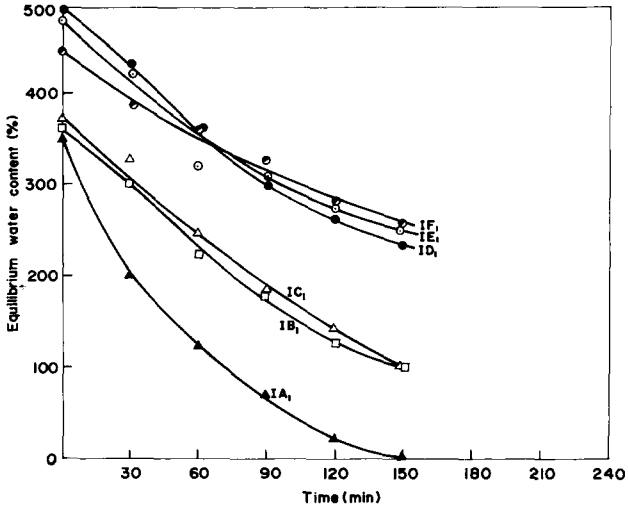

Figure 8 Effect of PHEMA variation on desorption studies of PHEMA/PVA semi-II-IPN

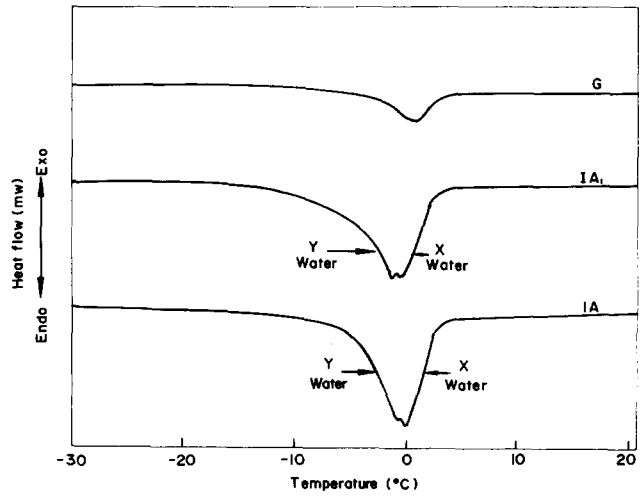

Figure 9 D.s.c. melting curves of water in PHEMA/PVA IPN

Table 2 Influence of solutes on swelling behaviour of PHEMA/PVA IPN system

Sample code	Percentage composition	Percentage of swelling in:				
		Water	10% urea	10% KI	10% D-glucose	10% NaCl
IIF_1	33PVA/67HEMA					
	2% BDDMA	155	182	223	126	97
IIF	33PVA/67HEMA					
	2% GLA/2% BDDMA	94	100	135	76	59
IA_1	50PVA/50HEMA					
	2% BDDMA	349	432	472	336	108
IA	50PVA/50HEMA					
	2% GLA/2% BDDMA	169	206	224	166	78
IF_1	67PVA/33HEMA					
	2% BDDMA	499	575	589	476	132
IF	67PVA/33HEMA					
	2% GLA/2% BDDMA	327	381	386	186	112
A	100 PVA					
	2% GLA	391	697	532	198	154
G	100 HEMA					
	2% BDDMA	30	40	44	22	17

Table 3 Glass transition temperature (T_g) and EWC of PVA/PHEMA IPN system

Percentage composition	Glass transition temperature, T_g (°C)		EWC	
	Without GLA	With GLA	Without GLA	With GLA
33PVA/67HEMA	80	89	160	100
50PVA/50HEMA	78	84	350	170
67PVA/33HEMA	83	85	500	330

is less than for semi-II-IPN (IA_1) and greater than the curve corresponding to the PHEMA individual network (G). The presence of merged double peaks and the difference in position and shape of peaks corresponding to IA and IA_1 is interesting. There are reports[34–36] on different thermodynamic states of water, i.e. free water, bound water, intermediate water, etc. For PHEMA crosslinked with ethyl dimethacrylate, Roorda *et al.*[37] have reported different states of water from double peaks of differential thermal analysis, but calorimetric analysis shows only a single class of water. They concluded it to be a continuous distribution of water molecules over all possible states.

In this study the PHEMA shows only a single peak with continuous variation of energy but the IPNs IA and IA_1 show merged double peaks with variation in position and shape. This probably proves the existence of at least two different classes of water. Although there are conflicting reports regarding different classes of water associated with hydrogels, the present observation of 'X' and 'Y' types associated with semi- and full-IPNs may be justified in respect of two networks being present. Detailed studies are required to offer a more valid explanation.

Effect of crosslinking

The glass transition temperature (T_g) and dynamic swelling behaviour can be controlled by crosslinking. From *Table 2*, it is clear that systems crosslinked with glutaraldehyde have higher T_g and low swelling ratio. Systems where PVA is not crosslinked have low T_g and higher swelling ratio, which makes it clear that those systems having higher polar segmental motion have higher EWC.

Surface morphology

The surface morphology of dry polymer films is shown in the form of scanning electron micrographs in *Figures 10–15*. *Figure 10* corresponds to the composition 33PVA/67HEMA showing a discontinuous pattern on the surface, where PVA is not crosslinked with GLA. Under the same conditions of polymerization and film forming, the surface appears smooth when PVA is crosslinked with GLA (*Figure 11*). *Figures 12* and *13* correspond to PVA/PHEMA 1:1 composition, which has a relatively smooth surface irrespective of crosslinking, and *Figures 14* and *15* show the surface morphology of the films corresponding to the composition 67PVA/-33PHEMA. These films also have smooth surfaces. It is noted that if the PVA content is higher, the film surface appears smoother. This is supported by the film-forming characteristics and flexibility of PVA-based systems.

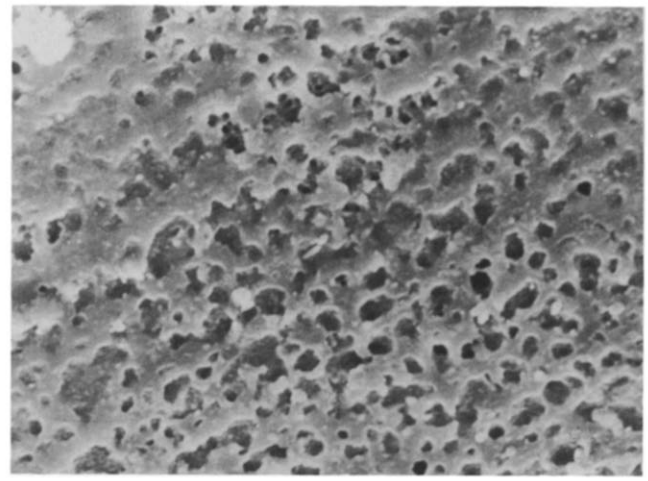

Figure 10 Scanning electron micrograph of 33PVA/67HEMA (2% BDDMA). (Magnification × 1447)

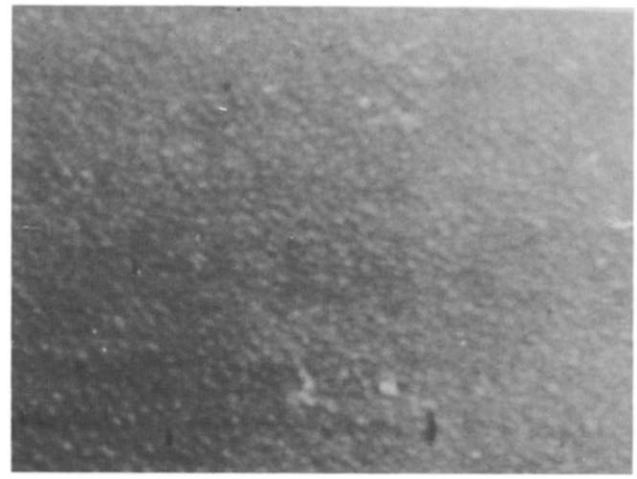

Figure 11 Scanning electron micrograph of 33PVA/67HEMA (2% GLA, 2% BDDMA). (Magnification × 1447)

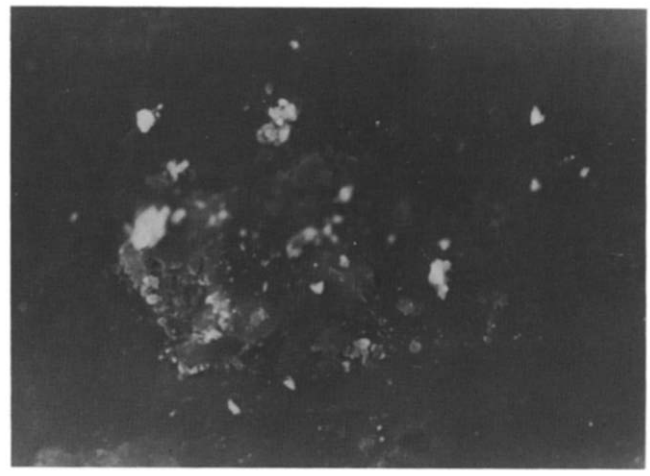

Figure 12 Scanning electron micrograph of 50PVA/50HEMA (2% BDDMA). (Magnification × 1447)

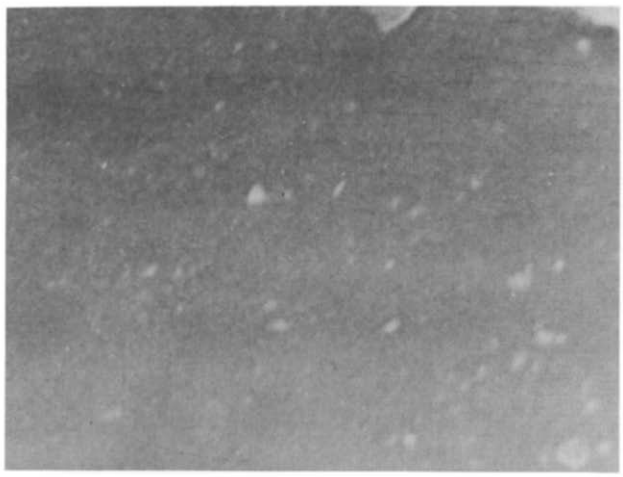

Figure 13 Scanning electron micrograph of 50PVA/50HEMA (2% GLA, 2% BDDMA). (Magnification × 1447)

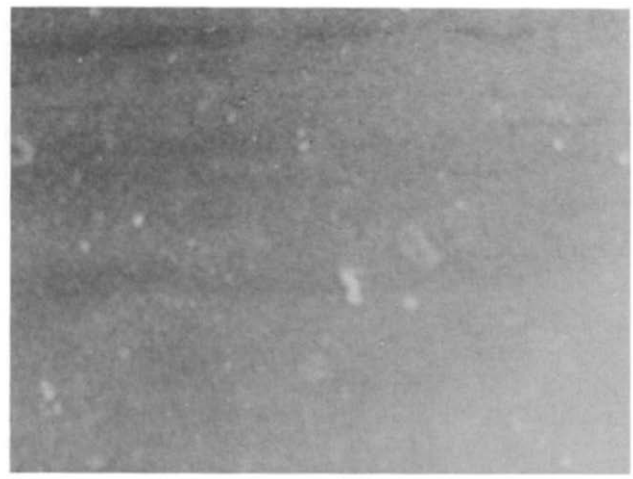

Figure 15 Scanning electron micrograph of 67PVA/33HEMA (2% GLA, 2% BDDMA). (Magnification × 1447)

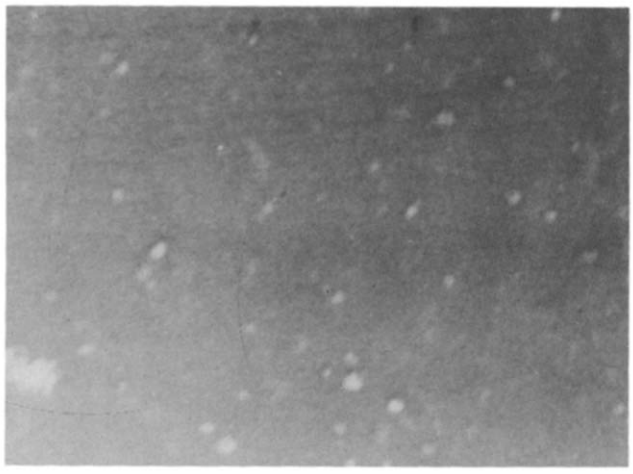

Figure 14 Scanning electron micrograph of 67PVA/33HEMA (2% BDDMA). (Magnification × 1447)

CONCLUSIONS

The use of interpenetrating and crosslinking techniques provides an interesting way of modifying the EWC in PHEMA. The incorporation of PVA into a PHEMA/PVA IPN hydrogel system shows extensive swelling and slow water desorption. The presence of solutes in the aqueous medium has a strong influence on the swelling properties of hydrogels. The existence of different classes of water in semi- and full-IPNs is shown by the water-melting curves obtained by d.s.c.

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REFERENCES

1 Peppas, N. A. and Yang, W. H. M. *Contact Intraoc. Lens. Med. J.* 1981, 7, 300
2 Lee, P. I., US Pat. 4 598 122, 1986
3 Ratner, B. D. In: 'Biocompatibility of Clinical Implant Materials', Vol. 2 (Ed. D. F. Williams), CRC Press, Boca Raton, FL, 1981, p. 145
4 Peppas, N. A. (Ed.) 'Hydrogels in Medicine and Pharmacy', Vol. 3: Properties and Applications', CRC Press, Boca Raton, FL, 1987
5 Hoffman, A. S. In: 'Macromolecules' (Eds H. Benoit and P. Remptt), Pergamon Press, New York, 1982, p. 321
6 Wichterle, O. and Lim, D. *Nature* 1960, **185**, 117
7 Refojo, M. F. and Yasuda, H. *J. Appl. Polym. Sci.* 1965, **9**, 2425
8 Peppas, N. A., Moynihan, H. J. and Lucht, L. M. *J. Biomed. Res.* 1985, **19**, 397
9 Andrade, J. D., Lee, H. B., Jhon, M. S., Kim, S. W. and Hibbs, J. B. *Trans. Am. Soc. Artif. Intern. Organs* 1973, **19**, 748
10 Macret, M. and Hild, G. *Polymer* 1982, **23**, 748
11 Corkhill, P. H., Jolly, A. M., Ny, C. O. and Tighe, B. J. *Polymer* 1987, **28**, 1757
12 Seiderman, M. US Pat. 3 271 657, 1973
13 Kabra, B. G., Gehrke, S. H., Hwang, S. T. and Ritsschel, W. A. *J. Appl. Polym. Sci.* 1991, **42**, 2409
14 O'Driscoll, J. H. and Isen, A. A. US Pat. 3 700 761, 1972; US Pat. 3 816 571, 1974
15 Sperling, L. H. 'Source-based Nomenclature of Polymer Blends, IPN's and Related Materials', Division of Polymer Chemistry Nomenclature Committee Document, 1984
16 Frisch, K. C. and Klempner, D. 'Recent Developments in Polyurethane and Interpenetrating Polymer Networks', Technomics, Lancaster, PA, 1988
17 Nishinari, K., Watase, M. and Ogino, K. *Polym. Commun.* 1983, **24**, 345
18 Lee, H. and Neville, K. In: 'Handbook of Plastics', Pasadena Technical Press, CA, 1971
19 Lee, P. I. US Pat. 4 559 186, 1985
20 Lee, P. I. US Pat. 4 619 793, 1986
21 Wichterle, O. *Encyclopaedia Polym. Sci. Technol. Hydrogels* 1971, **15**, 273
22 Ramaraj, B., Rajalingam, P. and Radhakrishnan, G. *J. Appl. Polym. Sci.* 1991, **43**, 23
23 Ramaraj, B., Rajalingam, P. and Radhakrishnan, G. 1st Asia Pacific Conference on Advances in Coating Technology, Singapore, 1991
24 Natchimuthu, N., Rajalingam, P., Radhakrishnan, G. and Joseph Francis, D. *J. Appl. Polym. Sci.* 1990, **41**, 3059
25 Ratner, D., Hoffman, A. S., Hanson, S. R., Harker, L. A. and Whiffen, J. D. *J. Polym. Sci. Polym. Symp. Ser.* 1979, **66**, 363
26 Kim, S. W., Cardinal, J. R., Wisniewski, S. and Zentner, G. M. *Am. Chem. Soc. Symp. Ser.* 1980, **127**, 347
27 Poh, B. T., Adachi, K. and Kotaka, T. *Macromolecules* 1987, **20**, 2563
28 Roorda, W. E., Bodde, H. E., De Boer, A. G., Bouwstra, J. A. and Junginger, H. E. *Pharm. Weekbl. Sci.* 1986, **8**, 165
29 Lee, P. I. *Polym. Commun.* 1983, **24**, 45
30 Refojo, M. F. *J. Polym. Sci. A-1* 1967, **5**, 3103

31 Dusek, K., Bohdanecky, M. and Vosicky, Y. *Coll. Czech. Chem. Commun.* 1977, **42**, 1599
32 Roorda, W. E., Bouwstra, J. A., De Vries, M. A., Kosho, C. and Junginger, H. E. *Thermochimica Acta* 1987, **112**, 111
33 Nosaka, A. Y. and Tanzawa, H. *J. Appl. Polym. Sci.* 1991, **43**, 1165
34 Lee, H. B., Jhon, M. S. and Andrade, J. D. *J. Colloid. Sci.* 1975, **51**, 558
35 Sung, G. K., Gregonis, D. E., Jhon, M. S. and Andrade, J. D. *J. Appl. Polym. Sci.* 1981, **26**, 3719
36 Janiguchi, Y. and Horigome, S. *J. Appl. Polym. Sci.* 1975, **19**, 2743
37 Roorda, W. E., Bouwstra, J. A., De Vries, M. A. and Junginger, H. E. *Biomaterials* 1988, **9**, 494