Preparation of Hydrophilic Polymer Networks by Post-Curing Reaction

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SYNOPSIS

Hydrophilic gels are a very important class of polymeric materials with extensive applications as biomedical products. The critical properties of hydrogels, such as sorption and desorption, mechanical behavior, swelling properties, etc., are controlled by network characteristics, i.e. degree of crosslinking and the density, distribution and length of crosslinks. Hydrogels prepared by copolymerization of 2-hydroxyethyl methacrylate (HEMA) with ethylene glycol dimethacrylate (EGDMA) have already been studied in detail. In this work, hydrophilic networks were prepared by crosslinking HEMA with EGDMA, and poly(2-hydroxy-ethyl methacrylate) (PHEMA) with diphenylmethane-4,4'-diisocyanate (MDI). The swelling properties of both types of networks were studied and the differences in behavior were attributed to the different techniques applied for network formation.

INTRODUCTION

The unique suitability of hydrogels as biomaterials is based on the favorable combination of the properties they display.[1] Biomedical applications of hydrogels include soft contact lenses, as well as artificial corneas, soft tissue substitutes, or burn dressings. Also, hydrogels may be impregnated with biologically active agents and serve as systems for controlled release.[2-11]

The latter application is perhaps the most important field of research and development. Peppas et al. developed new materials,[12-15] studied the solute and penetrant diffusion in swellable polymers,[12,16,17] and introduced a simplified equation describing solute release.[18,19] C. Migliaresi et al.[8,20] studied the water sorption and desorption in copolymers based on HEMA and methyl methacrylate, whereas J. D. Andrade dealt with stereoregular PHEMA polymers[21] and analyzed water in PHEMA by NMR methods.[22]

The above papers mainly concern the preparation, behavior, and analysis of hydrogels based on PHEMA prepared by crosslinking of HEMA with ethylene glycol dimethacrylate via a copolymerization reaction. These systems are characterized by a distribution of crosslinks that may be different from that of networks prepared by the postcuring reaction of PHEMA with a curing agent. Such a process has already been reported[23] for the preparation of crosslinked polystyrene. These polymers were called "isoporous" because the initial homogeneous conditions of the reaction are expected to lead to a uniform crosslink density and pore distribution.[24,25] Although pore size distribution cannot be determined directly, "isoporous" networks present interesting behavior, which deviates from that of conventionally prepared gels in the same crosslinker molar ratio. For example, the swelling capacity of polystyrene gels in toluene is higher than that of networks with the same degree of crosslinking but prepared by the use of divinyl benzene.

In this work PHEMA hydrogels were prepared by the crosslinking of a solution of PHEMA in dimethyl formamide (DMF) with a diisocyanate compound. The swelling behavior of these materials in

Table I Mixture for Copolymerization in Solution (Specimen E)

Component	Weight (g)
HEMA	10
DMF	10
EGMA	1
BPO	0.1

Journal of Applied Polymer Science, Vol. 45, 1005–1010 (1992)
 CCC 0021-8995/92/061005-06$04.00

Table II Polymerization Mixture for Postcured Samples (Specimen D)

1st Step (Polymerization)		2nd Step (Crosslinking)	
Component	Weight (g)	Component	Weight (g)
HEMA	10	PHEMA solution (50% in DMF)	20
DMF	10		
BPO	0.1		
1-Dodecanthiol	0.05	MDI	1.25

Table III Copolymerization Mixture for Preparation of Samples by Redox Initiation (Specimen R)

Component	Weight
HEMA	10
H_2O	4
EGDMA	1
$Na_2S_2O_5$	0.1
$K_2S_2O_8$	0.1

Table IV Mixture for Bulk Copolymerization (Specimen B)

Component	Weight
HEMA	10
EGDMA	1
BPO	0.1

various solvents was studied and was compared with that of the HEMA and EGDMA copolymers prepared in this study.

EXPERIMENTAL

The raw materials for the hydrogel preparation were the following: HEMA and EGDMA (Fluka AG, Switzerland); DMF and 1-dodecanthiol (Merck, W. Germany); diphenylmethane-4,4′-diisocyanate (MDI) (Bayer AG, W. Germany); and dibenzoyl peroxide (BPO) (purum Fluka). Deionized water and methanol were used for the swelling measurements. The copolymerizations were carried out as follows:

1. In DMF solution, at 80°C (specimen E)
2. In water solution, at 25°C (specimen R)
3. In bulk at 80°C (specimen B).

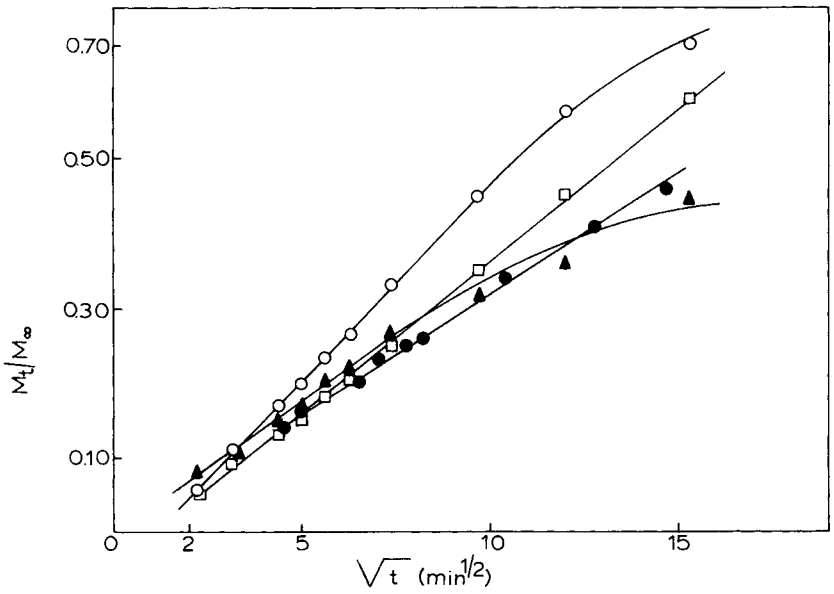

Figure 1 Water desorption at 23°C. Specimens: ○ R (redox), ▲ B (bulk), □ D (postcured), ● E (HEMA/EGDMA-MDI).

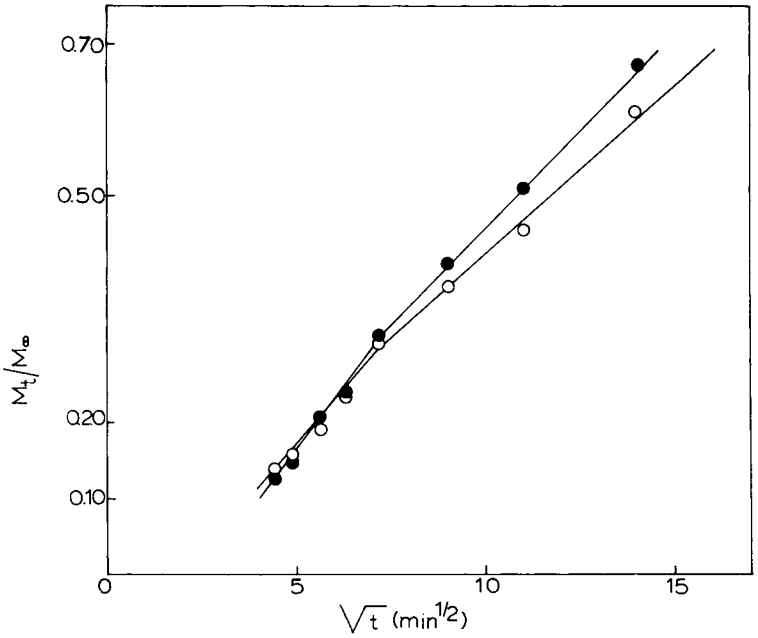

Figure 2 Water desorption at 20°C. Specimens: ○ E (HEMA/EGDMA-MDI), ● D (postcured).

The technique for the preparation of postcured samples included (a) solution polymerization of HEMA at 80°C and (b) crosslinking of the polymer with MDI at 25°C (specimen D). The reaction mixtures for each case are shown in Tables I–IV.

In all cases the mixture was purged with nitrogen to expel any oxygen that inhibits polymerization. The solutions were poured into Petri dishes and placed in an oven at 80°C or kept at room temperature. The solution of PHEMA in DMF, prepared from the mixture listed in Table II, was cooled to 25°C and a solution of MDI in DMF was added. Then the mixture was poured into polyethylene dishes, so that discs of crosslinked PHEMA were obtained. The gelling time was about 5 min. It should be noted that this latter technique, i.e. the postcuring reaction, seems to be versatile as it can give cast final products with various configurations.

The products containing DMF as a solvent (samples E and D) were dried slowly, since conditions that provide fast drying lead to severe cracking and damaging of the specimen. The removal of DMF appeared also to produce crazing of the samples. To avoid this, the specimens were dried in a vacuum

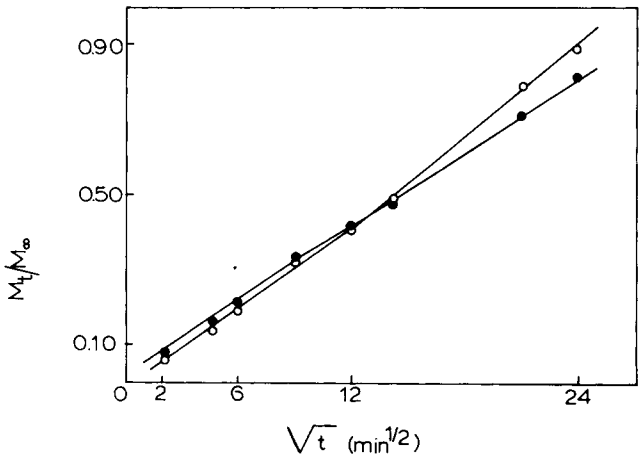

Figure 3 Water desorption at 37°C. Specimens: ● E (HEMA/EGDMA-MDI), ○ D (postcured).

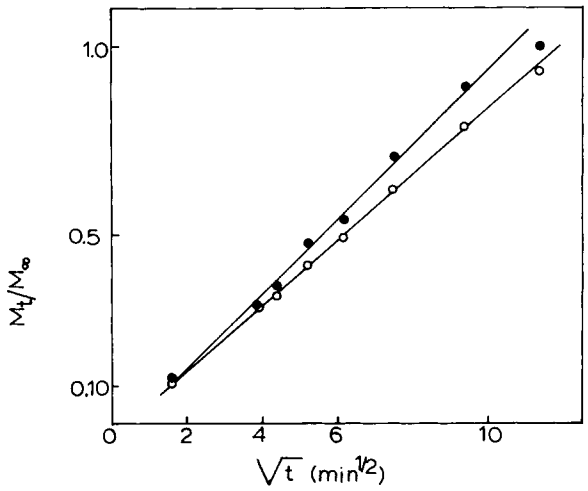

Figure 4 Water desorption at 50°C. Specimens: ○ E (HEMA/EGDMA-MDI), ● D (postcured).

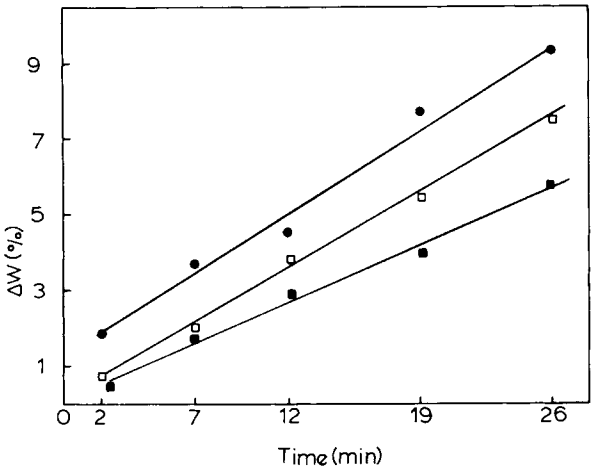

Figure 5 Methanol uptake versus time. Specimens: ● E (HEMA/EGDMA-MDI), □ D (postcured), ■ B (bulk).

oven, at 40°C for 48 h. After drying, they were immersed in deionized water and kept for several days, so that any impurity was leached out. The specimens were then immersed in various solvents, such as deionized water, MeOH, and DMF, at various temperatures and the weight increase was recorded. The desorption rate in swollen specimens was also determined at 23°C and 50% RH.

RESULTS AND DISCUSSION

The water desorption curves for the specimens prepared by solution and bulk polymerization are shown in Figure 1. It is evident that up to a desorption level of about 60%, linearity is established between desorption and the square root of time, for the specimens prepared by solution polymerization, whereas sample B shows different behavior, as linearity exists only up to about 30% water desorption.

The water sorption curves, at various temperatures, for specimens E and D are shown in Figures 2, 3, and 4. Figures 2 and 3 indicate a non-Fickian sorption for both specimens, despite the linearity of the two sections of the curves. It is evident that Fickian sorption appears for both specimens as the temperature rises at 50°C.

The swelling of hydrogels E, D, and B in solvents other than water is shown in Figures 5 and 6. Although methanol uptake is almost similar for all three specimens, the DMF sorption is different for the samples prepared in different ways. More spe-

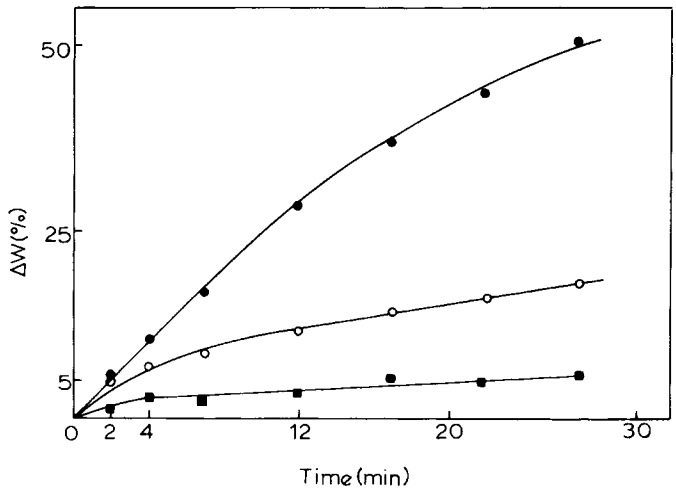

Figure 6 Swelling in DMF as a function of immersion time. Specimens: ● D (postcured), ○ E (HEMA/EGDMA-MDI), ■ B (bulk).

cifically, the postcured sample (specimen D) seems to swell more quickly and to a much higher equilibrium value.

The equilibrium swelling in water, for specimens E and D, is presented in Table V. A decrease of ultimate swelling with increasing temperature is evident for both specimens prepared by solution polymerization. Moreover, the equilibrium values are lower for the postcured specimen in the temperature range 20–50°C.

The swelling in methanol and DMF, for specimens E, D, and B, are presented in Table VI. It is evident that specimen B presents considerably lower swelling in both solvents. Furthermore, DMF seems to be a more effective swelling solvent compared with methanol. The swelling of the postcured sample in DMF seems to proceed faster than that observed in specimens prepared by copolymerization. However, sorption in methanol leads to lower swelling for the postcured specimen.

The results presented can be interpreted as follows: the non-Fickian behavior, clear in Figures 2 and 3, was normally to be expected. Similar results were reported by Lee[7] for PHEMA hydrogels loaded with various amounts of thiamine hydrochloride.

Fickian penetration with increasing temperature is due perhaps to increased chain mobility as the temperature rises. Moreover the temperature increase is accompanied by a decrease in the equilibrium sorption values for both types of specimens, as Table V indicates. These results are comparable to those reported by J. D. Andrade et al.,[21] who observed a decrease of the water fraction of tactic PHEMA in distilled water as the crosslinker concentration or the temperature increased.

The behavior of the postcured samples does not really deviate from that of the specimens crosslinked with EGDMA in solution, at least concerning the sorption–desorption of water and swelling in methanol. However, swelling in DMF is considerably enhanced for the above samples as Figure 6 and Table VI indicate. This could be attributed to the different chemical structure of the penetrants investigated.

Table V Water Sorption at Equilibrium for Various Specimens and Temperatures

		Percentage Weight Increase		
Specimen	Temperature (°C)	20	37	50
E		52.9	40.5	25
D		42.3	36	29.3

Table VI Swelling for Various Specimens in Methanol and DMF

	Percentage Weight Increase		
Specimen	MeOH (20°C, 26 min)	DMF (20°C, 27 min)	DMF (50°C, 48 h)
E	9.2	18	136.5
D	7.5	50	297
B	5.7	6	12.8

Thus, in the case of water and methanol, strong hydrogen bonding exists between their own molecules and the polymer chains. Such interactions are, of course, drastically reduced in DMF. Although hydrogen bonding is the predominant intermolecular interaction in the solvent, its role in the overall interaction between polymer and solvent is rather small.[26] Moreover, the higher sorption in DMF is in agreement with the high swelling of "isoporous" polystyrene networks in toluene, i.e. a nonpolar solvent.[23,24]

CONCLUSIONS

From the above results we can draw the following conclusions:

1. The two-step described process for producing hydrogels seems to be versatile, allowing the preparation of final products with several configurations (discs, cylinders, sheets, etc.)
2. The postcured specimens display much higher swelling (compared with hydrogels crosslinked with EGDMA) when immersed in DMF, where hydrogen bonding is eliminated.

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Received May 1, 1991
Accepted August 30, 1991