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Water sorption behaviour of polymeric systems based on tetrahydrofurfuryl methacrylate

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Earlier research has described the water absorption behaviour, drug release and biological properties of a room temperature polymerizing system based on poly(ethyl methacrylate) (PEM) powder and tetrahydrofurfuryl methacrylate (THFM) monomer. This work has been extended, with respect to water sorption behaviour, by replacing the monomer to various extents with hydroxyethyl methacrylate (HEMA), and poly(ethyl methacrylate) by ethyl methacrylate (EM)-THFM copolymers. Replacing the THFM with HEMA, and gelling with PEM, increased the diffusion coefficient progressively. The replacement of PEM by EM-THFM copolymers, when gelled with THFM monomer, substantially reduced equilibrium water uptake, and increased diffusion coefficients. However, with HEMA monomer, equilibrium uptake was unaffected, but the diffusion coefficient decreased with increasing THFM content of the copolymer. This is due to a complex interaction of THFM cross-linking the copolymer, and the effect of EM on the water uptake. Heat polymerizing the PEM-THFM system reduced equilibrium uptake and the diffusion coefficient, compared with the room temperature polymerizing system; this could reflect molecular weight differences.

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1. Introduction

Room temperature polymerizing systems based on poly(ethyl methacrylate) (PEM)-tetrahydrofurfuryl methacrylate (THFM) have been described previously [1–3]. They have been shown to have potential as cartilage repair materials [4–7], and for drug release [8, 9]. Also, Pearson *et al.* have shown the PEM-THFM system to be biocompatible with dental pulp [10]. The system has been shown to have distinctive water absorption properties [3], absorbing approximately 30% water; however, the sorption process is slow, with a diffusion coefficient of approximately 10^{-14} m^2 s^{-1}. Furthermore, there is evidence that the absorbed water is in clusters, in that the system remains rigid; i.e. it is not a hydrogel. Subsequent work has shown [11] that water uptake is critically dependent on the osmolarity of the external solution, uptake *decreasing* with increasing osmolarity of the external solution, until the equilibrium uptake levels out at about 3%. As uptake decreases, the diffusion coefficient, D, *decreases,* ultimately reaching a value of $D \approx 10^{-11}$ $m^2 s^{-1}$.

In the present study, the original PEM-THFM system has been varied, to investigate the effects on water uptake characteristics. This has been done by:

1. replacing PEM by ethyl methacrylate (EM)-THFM copolymers,
2. using these copolymer powders in conjunction with (a) THFM and (b) hydroxyethyl methacrylate (HEMA).
3. using PEM with HEMA-THFM comonomer mixtures.

2. Experimental procedure

PEM was obtained from Bonar Polymers Ltd (Ref: TS1364).

2.1. Preparation of EM-THFM copolymers

EM-THFM random copolymer beads of various compositions (10–70% THFM) were prepared by suspension polymerization. Typically, the mixed monomers (0.1 kg) containing 1% w/w benzoyl peroxide were suspended in an aqueous starch solution (18 g in 600 ml), contained in a reaction vessel equipped with a thermometer, reflux condenser, nitrogen inlet and mechanical stirrer. The suspension was stirred vigorously under an atmosphere of nitrogen, initially for 2 h at 60 °C. Then the temperature of the reaction flask was slowly raised to 90 °C, and held at this temperature for 1 h. The suspension was then poured into a large volume of hot water (5l) and stirred. The copolymer beads were allowed to settle out (~ 12 h). The beads were washed

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twice by decanting off the supernatant liquid, resuspended in hot water and allowed to settle out. The beads were then filtered off, washed with water and dried under vacuum, giving a yield of 55–60% copolymer beads. Finally, they were screened through a sieve (150 μm) and ball milled with 2% Lucidol CH50 (1:1 mixture of benzoyl peroxide and dicyclohexyl phthalate, Akzo Chemicals) for 6 h. This latter step was necessary because the beads were highly cross-linked, which inhibited residual peroxide extraction from the beads (*vide infra*).

2.2. Sample preparation

The three main groups of samples were prepared as follows.

2.2.1. EM-THFM copolymers

The copolymer powder was added to either THFM or HEMA monomer in the ratio 10 g copolymer of 6 ml monomer, each monomer containing 2.5% *N,N*-dimethyl-*p*-toluidine. Powder and monomer were thoroughly mixed to give a dough like consistency. The dough was put into a rectangular rubber mould (6 × 2 × 0.1 cm), sandwiched between two glass microscope slides (previously coated with releasing agent), and allowed to cure at room temperature.

2.2.2. HEMA-THFM comonomers

The comonomer was made by mixing equal volumes of HEMA and THFM with 2.5% v/v *N,N*-dimethyl-*p*-toluidine. Then PEM polymer was added to the comonomer, and the procedure in section 2.2.1 followed.

2.2.3. Heat polymerized PEM-HEMA and EM-HEMA random copolymers

PEM-HEMA samples were prepared as described in section 2.2.1, but with no *N,N*-dimethyl-*p*-toluidine in the monomer. The samples were cured by placing in an oven overnight at 80 °C. The EM-HEMA copolymers were made by first mixing the two monomers (50/50), adding 2% CH50, and then following the polymerization procedure described by Braden and Davy [11].

2.3. Water absorption

Rectangular specimens, approximately 1 mm thick, of the polymers were placed in distilled water maintained at 37 ± 0.5 °C. Each specimen was weighed prior to immersion in water, and then removed at intervals, blotted dry and weighed again as described previously [3]. Data were plotted as M_t/M_x versus $t^{1/2}$; where M_t is the mass uptake at time, t; M_x is the mass uptake at equilibrium, and t is time. Classical diffusion theory predicts that for the earlier stages of uptake

$$M_t/M_x = 2(Dt/\Pi l^2)^{1/2} \tag{1}$$

Hence if uptake is diffusion controlled, the plot should be linear, of slope, s

$$s = 2(D/\Pi l^2)^{1/2} \tag{2}$$

whence D may be calculated. For longer times up to equilibrium, the following equation applies

$$\frac{M_t}{M_x} = 1 - \frac{8}{\Pi^2}\sum_{n=0}^{n=x} 1/(2n+1)^2 \times \exp[-\Pi^2 D(2n+1)^2 t/4l^2] \tag{3}$$

From the value of D above, the experimental behaviour up to equilibrium can be compared with theoretical predictions. Computationally, it is easier to use the slope of the linear plot and Equation 2, which from Equation 3 gives

$$\frac{M_t}{M} = 1 - \frac{8}{\Pi^2}\sum_{n=0}^{n=x} 1/(2n+1)^2 \times \exp[-(2n+1)^2 \Pi^3 s^2 t/16] \tag{4}$$

Except at short times, usually the first term of the series is sufficient.

3. Results

Figs 1 and 2 are plots of per cent uptake as a function of time for the various EM-THFM copolymers doughed with THFM and HEMA, respectively. Table I summarizes equilibrium uptake and diffusion coefficient data, noting

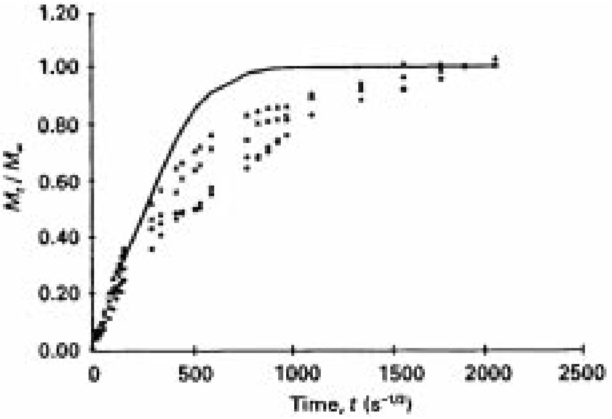

Figure 1 Plot of water uptake as M_t/M_x versus $t^{1/2}$ for EM-THFM copolymers doughed with THFM monomer: (–) mean theoretical value, (◆) 90% EM, (●) 70% EM, (×) 60% EM, (▲) 50% EM.

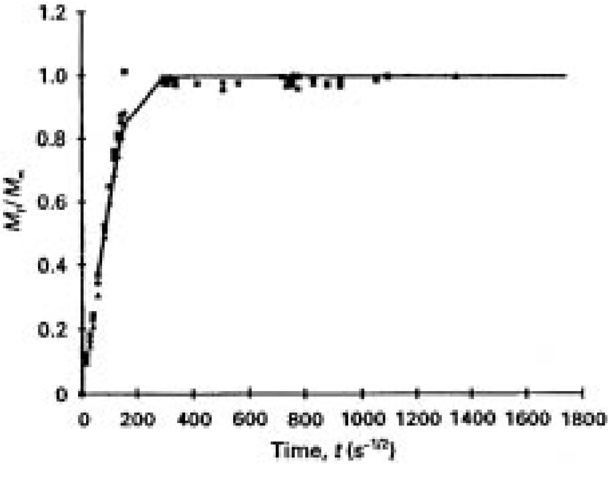

Figure 2 Plot of water uptake as M_t/M_x versus $t^{1/2}$ for EM-THFM copolymers doughed with HEMA monomer: (—) mean theoretical value, (–) 50% EM, (●) 90% EM, (▲) 30% EM, (■) 70% EM.

TABLE I Equilibrium uptake and diffusion coefficient data for EM-THFM copolymers

EM-THFM	Diffusion coefficient (10^{-11} m^2 s^{-1})		Equilibrium uptake (%)	
	THFM	HEMA	THFM	HEMA
100/0	[a]	3.0	11.9[b]	23.0
90/0	0.098	1.05	6.0	23.0
70/30	0.073	1.08	7.0	23.0
60/40	0.172	-	5.0	22.0
50/50	0.167	0.95	5.0	22.0
30/70	-	0.85	-	22.0

[a] Earlier work [3] gave a value of approximately 10^{-14} m^{2}s^{-1}.

[b] Not equilibrated at six-months (earlier work [3] showed the equilibrium value to be approximately 30%).

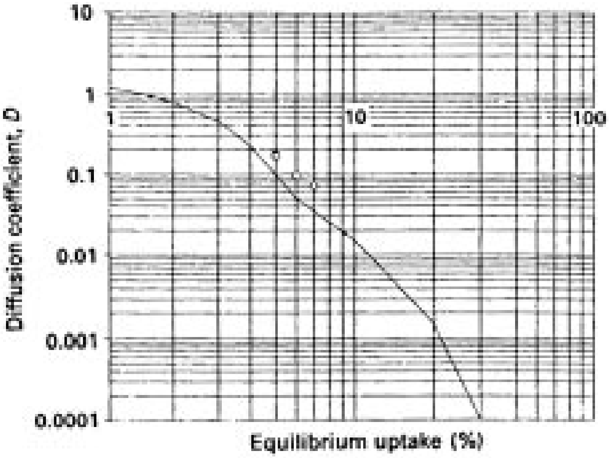

Figure 3 Plot of diffusion coefficient, D as a function of equilibrium uptake, C_0, for the EM-THFM copolymers doughed with THFM: (–) data for PEM-THFM where C_0 is controlled by the osmolarity of the external solution [11].

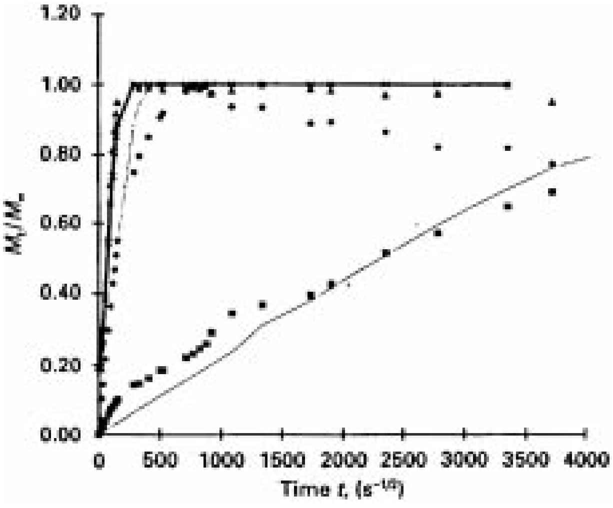

Figure 4 Plot of water uptake as M_t/M_x versus $t^{1/2}$ for PEM doughed with HEMA and a 50:50 THFM:HEMA mixture. Theoretical values: (- - -) M_t/M_x 50:50. (– × –) M_t/M_x HEMA. (—) M_t/M_x THFM. Measured values: (◆) M_t/M_x 50:50, (▲) M_t/M_x HEMA, (■) M_t/M_x, THFM.

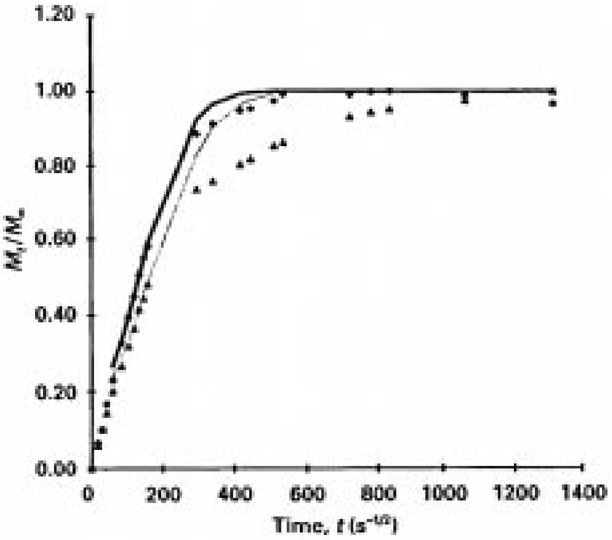

Figure 5 Plot of water uptake as M_t/M_x versus $t^{t/2}$ for a PEM-HEMA system and a EM-HEMA copolymer. Theoretical values: (—) M_t/M_x EM-HEMA, (- - -) M_t/M_x PEM-HEMA. Measured values: (◆) M_t/M_x EM, (▲) M_t/M_x PEM-HEMA.

TABLE II Effect of method of preparation on water sorption properties

Material	Curing method[a]	Equilibrium uptake (%)	Diffusion coefficient (10^{-11} m^2 s^{-1})
PEM-HEMA[b]	CC	20.8	1.01
PEM-THFM[b]	CC	11.33[c]	0.001 [3]
PEM-THFH-HEMA[b]	CC	9.71	0.775
PEM-HEMA[b]	HC	11.4	0.67
EM-THFM copolymer	HC	5.14	1.1
EM-THFM copolymer	HC	1.4	5.42

[a] CC, room temperature polyerimized; HC, heat polymerized.

[b] PEM polymer doughed with the monomer given.

[c] Not equilibrated in six months.

that PEM-THFM did not equilibrate after 18 months. Fig. 3 plots D as a function of equilibrium uptake, C_0, for the PEM-THFM system, superimposed on earlier data [1], where C_0 was controlled by the osmolarity of the external solution. Fig. 4 compares water uptake of PEM doughed, respectively, with HEMA and 50:50 THFM:HEMA monomer systems; Fig. 5 compares a heat polymerized PEM-HEMA system with a corresponding EM-HEMA copolymer. Diffusion coefficient and equilibrium uptake data are summarized in Table II.

4. Discussion

4.1. EM-THFM copolymers gelled with THFM monomer

The fact that the PEM-THFM system did not equilibrate at six months (Table I) is in accord with the earlier work of Patel and Braden [3]. However, when PEM is replaced by EM-THFM copolymers, three important effects are noted (Table I):

1. equilibrium uptake is drastically reduced.
2. $t^{1/2}$ plots are linear over a major portion of the uptake process (Fig. 1), and
3. diffusion coefficients are substantially increased.

It should also be noted that in the later stages of diffusion, conformity with Equation 2 improves as the

EM content of the copolymer increases, i.e. as the equilibrium uptake decreases.

These results have an interesting parallel to the effects of the osmolarity of the external solution reported previously [12]. Indeed, the data from Table I fit the diffusion coefficient, D, equilibrium uptake, C_0, data from earlier work, where C_0 is controlled by the osmolarity of the external solution (Fig. 3).

Initially, these results seem paradoxical; because poly(THFM) has a high water uptake, it might be expected that introducing THFM into the copolymer would *increase* uptake. However, the high water uptake of poly(THFM) should be seen in the context of the solubility of water in THFM monomer (or vice versa) being low. Hence the high water uptake of the polymer is consequent on the polymeric structure, although the mechanism is as yet unclear.

The introduction of EM into the polymeric bead phase evidently disrupts this aspect of the structure; furthermore the important effect of THFM is to cross-link the copolymer. Indeed, beyond 50% THFM, the copolymer could not gel with the monomers and was insoluble in chloroform. It therefore follows that while the PEM-THFM system is an interpenetrating network (IPN), where the PEM reduces water uptake to some extent, the EM-THFM copolymers give a ''cored structure'', with cross-linked beads in a poly(THFM) matrix. This was evident in a previous study on surface properties [13]. Because the beads are ∼ 60% v/v of the structure, this probably has the effect of limiting water uptake by limiting cluster size.

Hence, the similarities between the current work and that concerning the osmolarity of the external solution are due to the suppression of cluster formation, albeit by different mechanisms.

4.2. EM-THFM copolymers gelled with HEMA

In marked contrast to the systems with THFM as the monomer described above, the equilibrium uptake is sensibly independent of the copolymer used, as is the diffusion coefficient, although it is lower than when PEM is used. This is hardly surprising in the light of the known high hydrophilicity of HEMA.

Also, there is excellent agreement between experimental data and Equation 2 for the later stages of diffusion (Fig. 2).

4.3. PEM-50: 50 v/v mixture of THFM:HEMA

At six months the uptake of the mixed monomer system is less than either monomer used alone. Again, the presence of HEMA may well be offset by the cross-linking effect of the THFM; however, the presence of the HEMA has had a drastic effect on the diffusion coefficient, increasing it nearly a thousand-fold over the PEM-THFM system. This indicates that the *nature* of the sorption process has changed, and cluster formation no longer predominates. Indeed, Fig. 4 shows this system to be not too dissimilar to that with HEMA alone, although the data departs more from the predictions of Equation 2 than is the case with HEMA. These findings have important implications for the use of these systems for drug release, where HEMA could be used to modify the characteristics of the PEM-THFM system.

4.4. PEM-HEMA system compared with an equivalent EM-HEMA random copolymer

The copolymer has a much lower equilibrium uptake, but a similar diffusion coefficient to the corresponding PEM-HEMA mixed system.

5. Conclusions

Replacing PEM by EM-THFM copolymers profoundly affects the water sorption characteristics when used with THFM monomer. This is attributed to the presence of EM in the copolymer, which changes the water sorption characteristics observed with poly(THFM), and the THFM cross-linking the copolymer. However, when used with HEMA, the effects are comparatively small; the hydrophilicity of the HEMA is the predominant effect.

When a 50:50 HEMA: THFM monomer mixture is used with PEM, there is a reduction in equilibrium uptake when compared with HEMA, but little change in the diffusion coefficient; clearly HEMA has the predominant effect.

Copolymerizing EM with HEMA results in a lower equilibrium uptake, compared with a corresponding PEM-HEMA system, but gives a similar diffusion coefficient. However, it is clear (Table II) that heat curing the PEM-HEMA system gives lower equilibrium uptake compared with the room temperature polymerized materials.

Acknowledgements

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