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Copolymer hydrogels of 2-hydroxyethyl methacrylate with *n*-butyl methacrylate and cyclohexyl methacrylate: synthesis, characterization and uptake of water

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Abstract

The bulk free radical copolymerizations of 2-hydroxyethyl methacrylate (HEMA) with *n*-butyl methacrylate (BMA) or cyclohexyl methacrylate (CHMA) were studied over the composition mole fraction interval of 0–1 for HEMA in the monomer feed. The ^{13}C NMR (125 MHz) spectra of the copolymers were analysed to determine the copolymer composition and the stereochemical configuration of the copolymers. The terminal model reactivity ratios of HEMA and BMA were found to be $r_{HEMA} = 1.73$ and $r_{BMA} = 0.65$ and for HEMA and CHMA, $r_{HEMA} = 1.26$ and $r_{CHMA} = 0.31$. The BMA and CHMA homopolymers were found to be predominantly syndiotactic with isotacticity parameters of $\theta_{BB} = 0.18$ and $\theta_{CC} = 0.19$, respectively. The copolymers were also found to be predominantly syndiotactic, indicating a strong tendency for racemic additions of the monomers in the formation of the copolymers. The diffusion of water into cylinders of poly(HEMA-co-BMA) and poly(HEMA-co-CHMA) was studied over a range of copolymer compositions and was found to be Fickian. The diffusion coefficients of water at 37°C were determined from swelling measurements and were found to vary from 1.72×10^{-11} m^2 s^{-1} for polyHEMA to 0.97×10^{-11} m^2 s^{-1} for poly(HEMA-co-BMA) having a mole fraction $F_{HEMA} = 0.80$ and to 0.91×10^{-11} m^2 s^{-1} for a poly(HEMA-co-CHMA) also having $F_{HEMA} = 0.80$. The mass of water absorbed at equilibrium relative to the mass of dry polymer varied from 58.8 for polyHEMA to 27.2% for poly(HEMA-co-BMA) having $F_{HEMA} = 0.85$ and to 21.3% for poly(HEMA-co-CHMA) having $F_{HEMA} = 0.80$. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Mass uptake; Diffusion coefficients; Equilibrium water uptake

1. Introduction

2-hydroxyethyl methacrylate (HEMA) copolymers have found numerous medical applications due to their acceptable biocompatibility [1–3]. Amongst other applications, these copolymers have been identified as having potential for use in controlled release drug delivery systems [4–6]. In these controlled release systems, the drug is immersed within the core of the glassy polymer, and, as body fluids migrate into the polymer, plasticizing it, the trapped drug is allowed to diffuse through the swollen hydrogel matrix. Thus, the rate of diffusion of water into the polymer controls the rate of release of the drug, and is dependent on the copolymer composition and microstructure, which are features determined by the kinetics of the polymerization of the comonomers. The diffusion of water into the polymer matrix can also be influenced: by the polarity of the polymer segments; by the glass transition temperature of the polymer; by the flexibility of the polymer backbone; by the cross-link density and interchain interactions; by the molecular weight of the polymer; by the degree of chain branching; and by the presence of bulky comonomer pendant groups.

In the controlled delivery systems based on hydrogels, the release of the drug occurs by the diffusion of the drug through the polymer, plasticized by body fluids, in response to a decreasing concentration gradient away from the glassy core of the polymer matrix. The diffusion of body fluids (water) into the polymer is the controlling step in the release process, since the drug diffuses much faster from the rubbery regions of the polymer than it does from the glassy core. The glass transition temperature of the polymer is lowered by the absorbed water in the rubbery regions, resulting in a significant increase in the segmental mobility of the polymer chains, thus facilitating the passage of the drug through the matrix.

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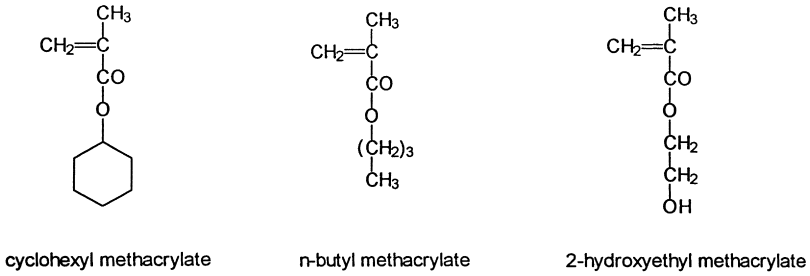

Fig. 1. Structures of the comonomers.

The rate of diffusion of water into a copolymer, as well as the equilibrium amount of water which can be absorbed by the matrix, is dependent on the nature of the comonomers present and on the comonomer composition. In the present study, the copolymers of HEMA with both *n*-butyl methacrylate (BMA) and cyclohexyl methacrylate (CHMA) have been investigated because of their potential use in drug delivery systems where the release rate of the drug needs to be modified from that of polyHEMA. The structures of the repeat units in the polymers are presented in Fig. 1. The distinguishing features of the three monomers are the hydrophilic polar hydroxy group of the HEMA monomer; the hydrophobic side-chain of BMA; and the bulky hydrophobic pendent ring of CHMA. As the hydrogel matrix is prepared by the bulk copolymerization, the properties of the matrix are critically dependent on the mechanism and kinetics of the copolymerization reaction.

Thus, one of the aims of the present study was to investigate the mechanism of the copolymerizations of HEMA with BMA and CHMA at low conversions over composition intervals of 0–1 mole fraction HEMA. This information can then be used to predict the compositional microstructure of the polymer matrices, which are formed when the copolymerizations are carried out to complete conversion. The second aim of the study was to investigate the stereochemical structure of the copolymers, which can play a role in determining the glass transition temperature of the matrix. Finally, it is of interest to study the effect that increasing proportions of the non-polar monomers have on the diffusion coefficient for water and the mass uptake of water at equilibrium in the HEMA copolymers.

2. Experimental

2.1. Copolymer synthesis

Stabilized BMA and CHMA (Aldrich Chemical Company) were purified by chromatography using anhydrous Al_2O_3 (neutral, Merck). Stabilized HEMA (Ubichem Ltd.) was purified immediately before use by vacuum distillation (<10 Pa) at 50°C, with only the middle fraction used experimentally. The purity of the monomers was confirmed by NMR analysis.

The monomers were weighed into a 250 ml Pyrex glass ampoule to give the desired mole fractions of the monomers, f_{HEMA} and f_{BMA} or f_{HEMA} and f_{CHMA}, and a total bulk mixture weight of 20 g. An amount of freshly recrystallized and dried benzoyl peroxide (BPO) initiator was weighed into the ampoule to give a concentration of 0.08 wt.% based on the total mass of the monomers present. The ampoules were then degassed on a vacuum line at a pressure of less than 5×10^{-2} Pa, using four freeze–thaw–degas cycles to remove oxygen from the reaction mixture. The ampoules were then sealed under vacuum.

Bulk polymerizations were carried out at 60°C until conversions of $\approx 5\%$ were achieved. The copolymers were then purified by reprecipitation in a suitable solvent/non-solvent system. The system used for the homopolymer of CHMA was tetrahydrofuran/methanol, and for BMA and all of the copolymers, the system used was acetone/*n*-hexane:acetone (9:1).

2.2. Copolymer characterization

^{13}C NMR spectra acquired for composition and tacticity studies were recorded at 50°C using 5% (w/v) solutions in $CDCl_3$/DMSO-d_6 mixed solvent on a Bruker AMX 500 spectrometer (125 MHz for carbon). The spectra were acquired with the inverse gated decoupling with approximately 500 accumulations per spectrum, each containing 32K data points. The pulse program used a 90° pulse angle with a 12 s recycle delay, which was equal or greater than five times T_1 for the slowest relaxing carbon in the polymer.

2.3. Preparation of copolymer cylinders for diffusion measurements

Cylindrical samples of the copolymers, polymerized to a high conversion, were prepared for diffusion studies in cylindrical Teflon moulds. (Cylindrical samples were chosen because they fit neatly into the NMR resonator used for imaging studies of the diffusion process.) The monomers were weighed into a 25 ml Pyrex glass flask in the required mole ratios and 0.08 wt.% BPO was added, based on the mass of the monomers. The mixture was shaken until the BPO had dissolved, and then it was poured into the Teflon mould which had an internal diameter of

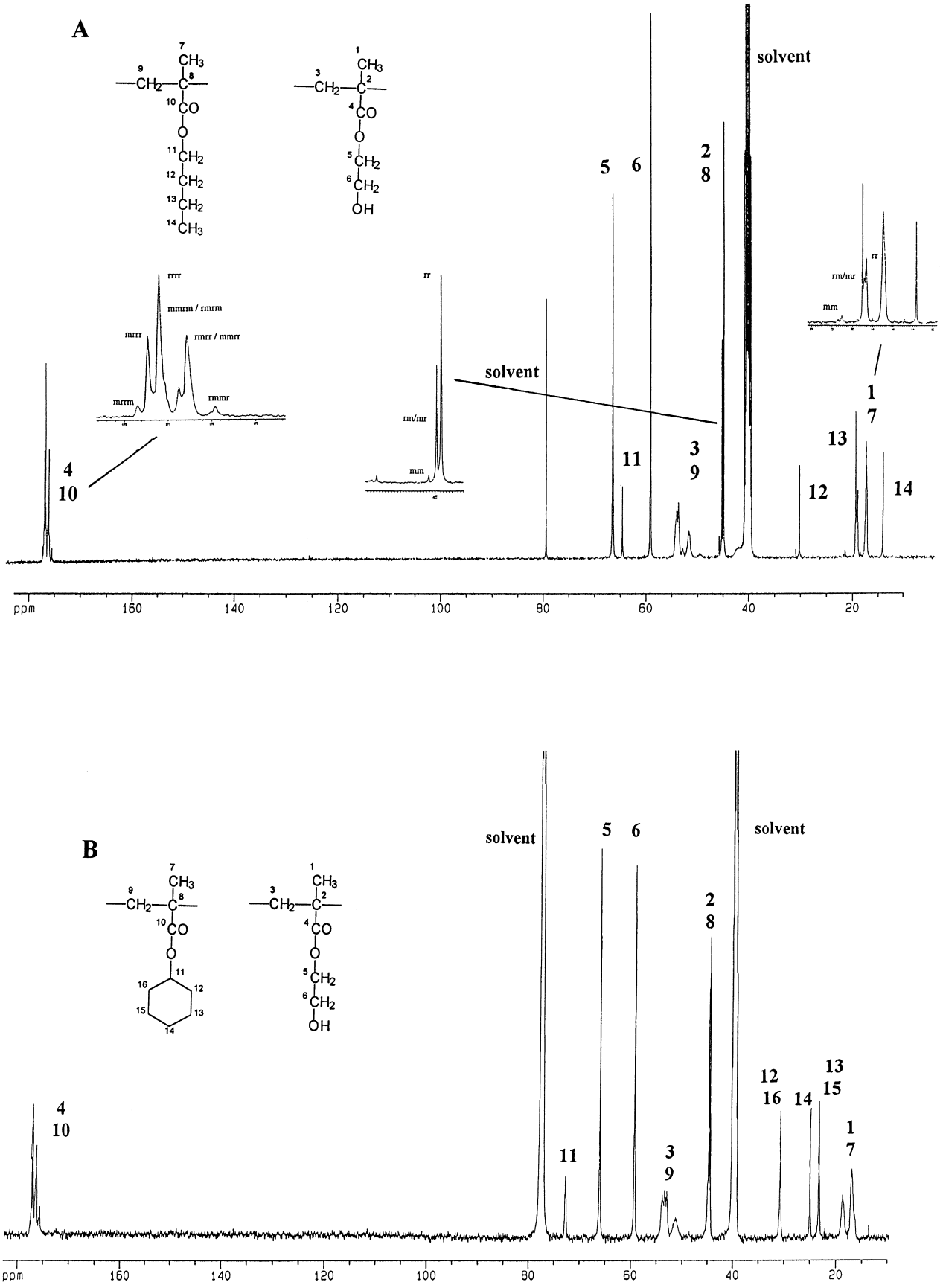

Fig. 2. Typical ^{13}C NMR spectra for the copolymers of (A) BMA/HEMA and (B) CHMA/HEMA in $CDCl_3$–DMSO mixed solvent at 50°C.

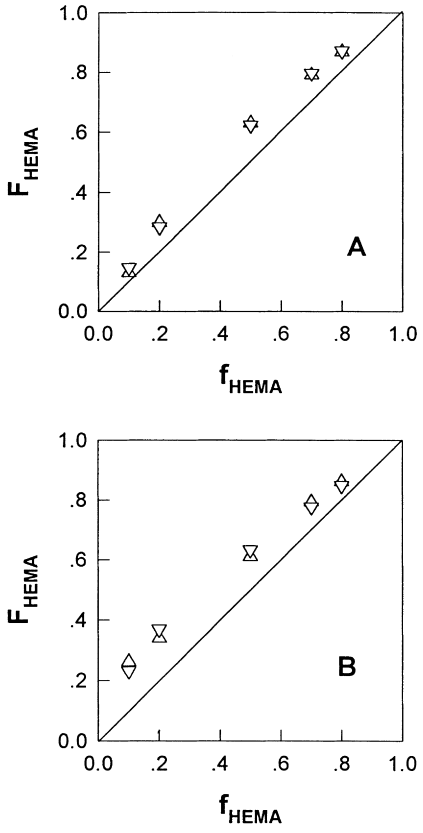

Fig. 3. Experimental values (△) and terminal model predictions (▽) for the HEMA copolymer mole fractions, F_{HEMA}, and feed mole fractions, f_{HEMA}, for polymerizations at 60°C: (A) BMA/HEMA; and (B) CHMA/HEMA.

10 mm and length 40 mm. The cylindrical mould was closed with a cap containing a small hole, to allow excess mixture to drain out of the cylinder. The polymerization was forced to complete the conversion of monomer to polymer in a vacuum oven using the following temperature/time protocol; the samples were held initially at 45°C for 6 h, then at 60°C for 18 h, 70°C for 4 h, 80°C for 4 h, 100°C for 2 h, and finally at 120°C for 12 h. This polymerization protocol leads to the formation of a polymer cylinder without the generation of excessive heat, which could result in the formation of bubbles or the loss of optical clarity. After polymerization, the polymer cylinders were removed from the Teflon moulds, the absence of the monomer was confirmed by FT-NIR analysis, and the ends were ground to a smooth, flat finish. The dimensions of the finished cylinders were $35.0 \times 10.0\ mm^2$.

2.4. Water uptake measurements

The copolymer cylinders prepared to 100% conversion were placed in $20 \times 4\ cm^2$ stoppered tubes filled with distilled water, in a water bath at 37 ± 1°C to simulate the physiological temperature condition. The cylinders were then placed on plastic mesh discs, about half-way up the tubes to ensure maximum exposure of the cylinders to the water. The polymers were removed, dried and weighed, initially every 15 min for 12 h, and then hourly after this, until equilibrium was approached.

3. Results and discussion

3.1. Copolymer microstructure determination

^{13}C NMR spectroscopy was used to characterize the compositions and tacticities of the low conversion copolymers. The T_1 values were determined using the inversion-recovery method, and the slowest relaxing carbons in the copolymers were found to be the quaternary carbons on the polymer backbones. For the copolymers, these quaternary carbon T_1 values at 50°C were: CHMA/HEMA, $T_1 = 1.5$ and BMA/HEMA, $T_1 = 2.4$ s.

Typical spectra obtained under these conditions for the two copolymers are shown in Fig. 2. The peaks in the spectrum were assigned by the application of the DEPT technique and have been labelled on the spectra according to the structure of the repeat units in the polymer chain.

3.2. Copolymer composition

The backbone carbons (C^1–C^4) are common to each of the monomers but the remaining carbons are unique to each monomer. Therefore, the proportions of the two monomers in the copolymers prepared at low conversion can be found from an analysis of these peak areas. It was found that the various combinations of peak intensities gave similar results for the copolymer compositions, but the most reliable estimates of the mole fractions can be obtained through the use of well resolved peaks. For example, the mole fraction of the BMA in the BMA/HEMA copolymer, F_{BMA}, can be found from the C^{11} peak of BMA and the C^6 of HEMA according to the following equation:

$$F_{BMA} = \text{Area } C^{11}/(\text{Area } C^{11} + \text{Area } C^6) \quad (1)$$

The mole fractions of CHMA present in the CHMA/HEMA copolymers, F_{CHMA}, were similarly determined using well resolved peaks, such as C^{11} and C^6 in Fig. 2(B). F_{HEMA} in the two series of copolymers was obtained from F_{BMA} or F_{CHMA}.

3.3. Reactivity ratios

The comonomer feed and the copolymer composition informations were used to perform NLLS analyses for the terminal [7,8] and penultimate [8,9] models on both sets of copolymerization data. From statistical analyses using the *F*-test [8], it was determined that the terminal model provided an adequate description of the polymerization data for both copolymerizations. The best values of the reactivity ratios calculated for the terminal model were; $r_{BMA} = 0.65$ and $r_{HEMA} = 1.73$ for BMA/HEMA, and $r_{CHMA} = 0.31$ and $r_{HEMA} = 1.26$ for CHMA/HEMA. Fig. 3 shows a comparison of the experimental and the predicted

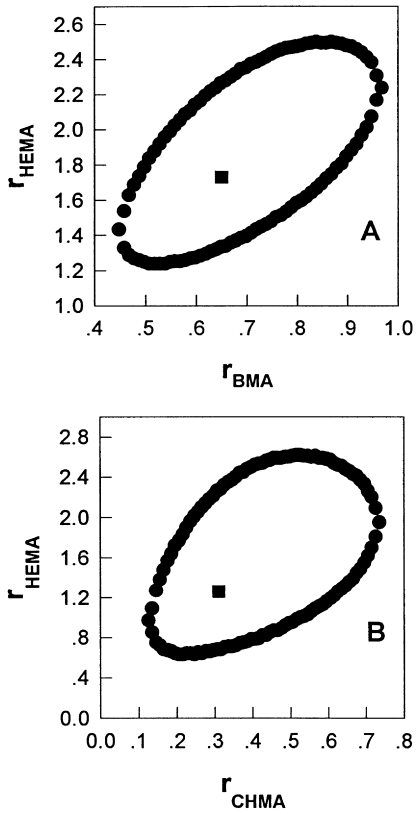

Fig. 4. Confidence ellipses (95%) for the terminal model reactivity ratios of (A) BMA/HEMA and (B) CHMA/HEMA. Best values of the reactivity ratios (■) at 60°C.

copolymer composition data. The extent of the deviation of the two polymerizations from ideal behaviour is relatively small, as is evident in the figure. The ellipsoids for 95% confidence in the calculated reactivity ratios for the fits to the terminal model are expressed as joint confidence intervals [8], and are presented in Fig. 4.

The products of the two reactivity ratios for the copolymerizations are BMA/HEMA = 1.12 and CHMA/HEMA = 0.39. This indicates that the BMA/HEMA copolymers form a close to statistical copolymer, with a small tendency for HEMA to add, in preference to BMA. On the other hand, the CHMA/HEMA copolymerizations show a slight tendancy towards alternation, perhaps indicating that the "bulkiness" of the side-chain of the CHMA monomer inhibit slightly the addition of this monomer to a CHMA chain-end radical. Varma and Patnaik [10] have previously reported that for HEMA/acrylate copolymerizations, reactivity decreases with increasing size (bulkiness) of the acrylate side-chains.

The sequence triads provide a measure of the distribution of the monomers in the polymer chain. The triad sequence distributions were calculated from the reactivity ratios and the instantaneous feed compositions [8]. The predicted proportions of each triad are presented graphically in Fig. 5. (Here, for example, the sequence in which a BMA unit has two HEMA neighbours has been identified as HBH, and the corresponding fraction of BMA units with two HEMA neighbours has been identified as F_{HBH}. The fractions of the other two possible B sequences, HBB and BBB, have been characterized by the fractions F_{HBB} and F_{BBB}, respectively. A similar terminology has been used for the HEMA sequences and for the CHMA/HEMA copolymers where C has been used to identify a CHMA unit).

The diagrams in Fig. 5 highlight the differences in the sequence distributions for the two series. For example, it is clear from an examination of Fig. 5(B) and (D) that, at all feed compositions, F_{HHH} is lower for CHMA/HEMA than for BMA/HEMA. For high HEMA feed contents (f_{BMA} or $f_{CHMA} < 0.2$), F_{HHH} falls almost linearly with increasing BMA or CHMA mole fraction, and at f_{BMA} or $f_{CHMA} = 0.2$, $F_{HHH} < 0.8$ for both systems. Thus for these copolymers, it may be expected that both the rate of diffusion of water and the mass fraction of water taken up at equilibrium would be significantly lower than for polyHEMA.

From Fig. 5(A) and (C), in the composition region f_{BMA} or $f_{CHMA} < 0.2$, single unit triad sequences of BMA and CHMA predominate in the copolymers.

3.4. Polymer stereochemistry

The α-methyl, carbonyl and quaternary carbon peaks are sensitive to the tactic triad distribution in methacrylate polymers [11]. These tacticity splittings are evident in the spectra for both of the copolymers shown in Fig. 2, and are highlighted in the expanded spectra shown in Fig. 2(A) for a BMA/HEMA copolymer. An analysis of the spectra showed that the copolymers are predominantly syndiotactic with the tactic triad fractions relatively insensitive to the feed composition for the BMA copolymers (see Fig. 6(A)), as has been found for several other methacrylate copolymers [12–14]. However, the tacticity triad fractions for the CHMA copolymers showed a systematic dependence upon the copolymer composition (see Fig. 6(B)), which is probably associated with the non-polar, bulky nature of the cyclohexyl ester group exhibiting a preference for racemic configurations for adjacent HEMA units.

The configurational sequence distribution in the homopolymers can be described by Bernoullian statistics [11]. The isotacticity parameters, θ, for the diad sequences in the homopolymers were determined for this model from an analysis of the NMR spectra and found to be $\theta_{BB} = 0.18$ for polyBMA and $\theta_{CC} = 0.19$ for polyCHMA. For comparison, the value of θ_{HH} obtained by Whittaker et al. [14] for polyHEMA was $\theta_{HH} = 0.25$, and Ghi et al. [13] have reported a value of $\theta_{TT} = 0.24$ for poly(tetrahydrofurfuryl methacrylate), polyTHFMA, indicative of the tendancy for the monomer additions in free radical homopolymerizations of methacrylic acid based monomers to be racemic. In the case of the copolymers of HEMA with BMA and CHMA, the tendency for the additions to be racemic is greater for the CHMA/HEMA system, as can be seen from a comparison of the plots in Fig. 6.

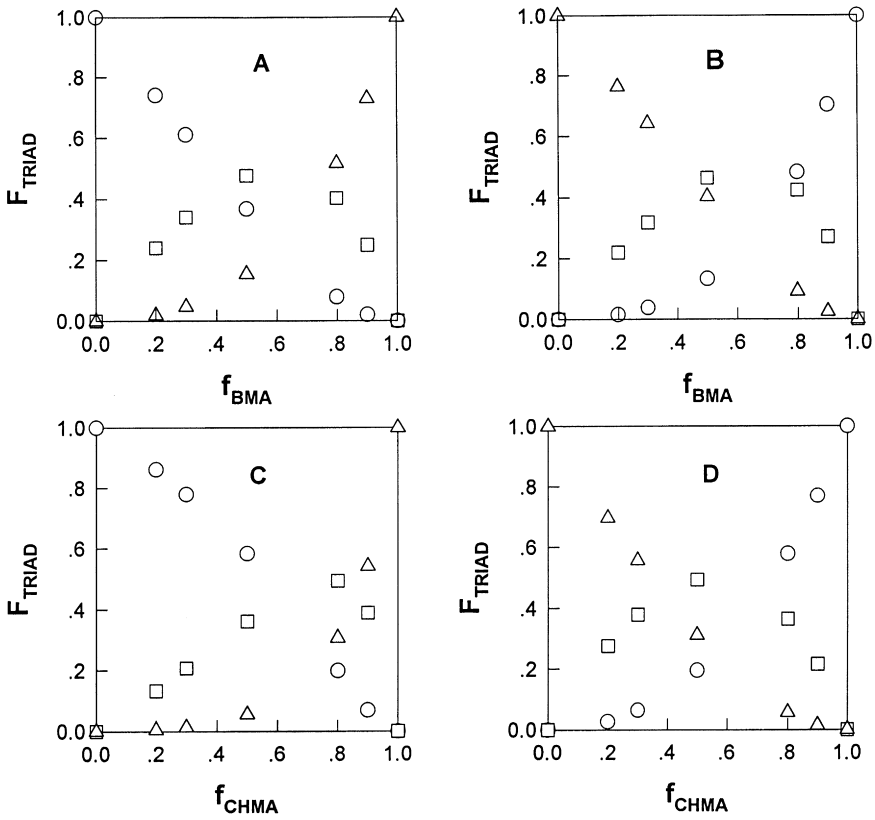

Fig. 5. Polymer triad fraction distributions, F, versus comonomer feed mole fractions, f, for: (A) BMA/HEMA, F_{HBH} (○), $F_{HBB+BBH}$ (□), F_{BBB} (△); (B) BMA/HEMA, F_{BHB} (○), $F_{HHB+BHH}$ (□), F_{HHH} (△); (C) CHMA/HEMA, F_{HCH} (○), $F_{HCC+CCH}$ (□), F_{CCC} (△); and (D) CHMA/HEMA, F_{CHC} (○), $F_{HHC+CHH}$ (□), F_{HHH} (△).

3.5. Predictions for high conversion copolymers

The change in the compositional microstructure with conversion can be calculated for both series of copolymers using the integrated form of the copolymer equation for the terminal model. Fig. 7 shows the instantaneous copolymer composition as conversion increases, for an initial feed composition of $f_{HEMA} = 0.8$. There is a slight decrease in the HEMA content of the instantaneous polymer being formed over the conversion range 0–80%, but above 90% conversion, the instantaneous HEMA content of the copolymer begins to decrease noticeably. However, the polymers showed no visual evidence of phase separation for comonomer mixtures polymerized to complete conversion. For the CHMA/HEMA copolymerizations, the HEMA monomer begins to be depleted at a slightly lower conversion than that for the corresponding BMA/HEMA copolymers. The differences between the BMA and CHMA copolymers result from the slightly higher relative reactivity of HEMA in the CHMA copolymers.

3.6. Water absorption by copolymer cylinders

Diffusion of water into polymers has been reported to occur between the two limiting cases, Fickian, or Case I diffusion and Case II diffusion [15]. For Fickian diffusion, the concentration gradient is the driving force for the diffusion and occurs when the rate of diffusion of the penetrant is much slower than the rate of relaxation of the polymer chains. In Case II diffusion, the rate of relaxation is slow relative to the rate of diffusion of the penetrant, so the relaxation (or mobility) of the polymer chains is the controlling force for diffusion. The anomalous region in between the extremes of Case I and Case II is known as Case III diffusion.

PolyHEMA has been previously reported [4] to follow Fickian or Case I kinetics, with a diffusion coefficient, D, of $4.78 \times 10^{-10}\ m^2\ s^{-1}$ for water in a very lightly cross-linked polymer at 34°C [4]. Gerhke et al. [16] have carried out a detailed investigation into polyHEMA sheets, and reported that the diffusion is Fickian at low mass uptake. However, they observed a change in the trend in the data at the point at which the glassy core disappeared, which was consistent with an increase in the water mass uptake rate. They determined the diffusion coefficients for water in polyHEMA in the absence of an added cross-linker over a range of temperatures from 4 to 88°C. In their calculations, the value of the diffusion coefficient was determined only using data for the region of the mass uptake curves before the disappearance of the glassy core.

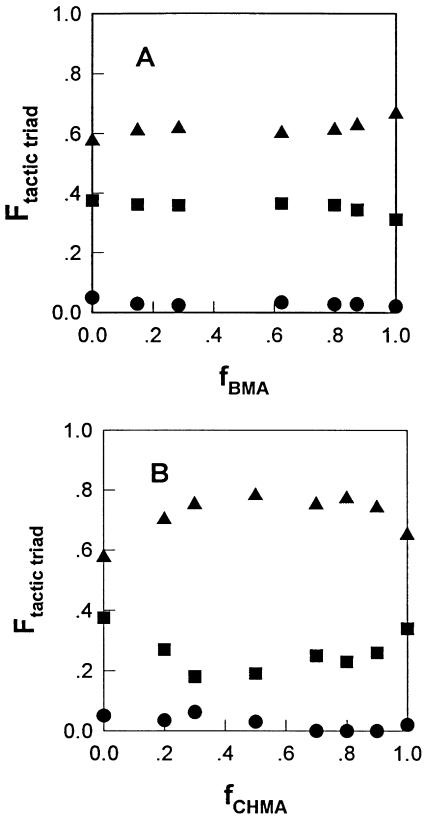

Fig. 6. The stereochemical polymer triad fraction, F, versus copolymer composition mole fraction, f, for (A) BMA/HEMA and (B) CHMA/HEMA F_{rr} (▲), F_{rm} (■), F_{mm} (●).

An interpolated value of the diffusion coefficient of 1.5×10^{-11} m^2 s^{-1} at 37°C was determined from an Arrhenius fit to the diffusion coefficient data of Gerhke et al. [16]. More recently, we have reported an NMR imaging study of the diffusion of water into HEMA polymers at ambient temperature [17] from which we obtained a diffusion coefficient for water of 1.5×10^{-11} m^2 s^{-1}.

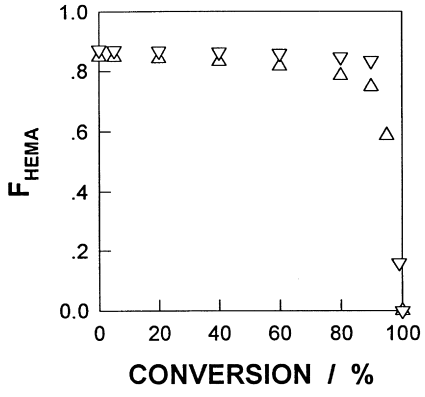

Fig. 7. The variation in the instantaneous copolymer mole fraction, F, for BMA/HEMA (▽) and CHMA/HEMA (△) as the conversion increases for an initial comonomer feed composition of $f_{HEMA} = 0.8$.

3.7. Measurements of diffusion coefficients in cylinders

The copolymers studied here are amorphous, and so isotropic diffusion can be assumed to apply. Ghi et al. [17] have shown that for such a matrix, the mass uptake of the penetrant by diffusion into an infinite cylinder of radius, a, can be represented by Eq. (2).

$$M_t/M_\infty = 1 - \sum_{n=1\rightarrow\infty} 4/\beta_n^2 \exp(-D\beta_n^2 t/a^2) \quad (2)$$

where t is the time for which the penetrant diffusion has occurred, M_t and M_∞ are the mass uptakes at time t and at equilibrium, respectively, D is the diffusion coefficient, and β_n are the roots of the zero-order Bessel function $J(\beta_n) = 0$.

The mass uptake data for the BMA/HEMA and CHMA/HEMA copolymers are shown in Figs. 8 and 9, respectively. The range of copolymer compositions investigated was limited to comonomer mole fractions up to 0.2, because this range corresponds to the greatest variation in the mass uptake of water per unit mass of polymer. The curves in Figs. 8 and 9 indicate that as the comonomer content of the polymer increases, the initial rate of increase in the mass of the cylinder decreases, as does the equilibrium mass uptake. The data in these figures were fitted to Eq. (2) over the range of diffusion times using a least squares curve fitting procedure [17] in which D was the determined parameter.

The results for the data fit for polyHEMA are shown in Fig. 10(A) for the curve fit in which mass uptake data over the full range were analysed. A section of the hypersurface for the curve fit is shown in Fig. 10(B), which was used to estimate the error in the value of D. Fig. 11(B) shows that the minimum in the hypersurface is clearly defined, which was also found to be the case for the curve fits of the copolymers. The best value of the diffusion coefficient obtained from the curve fit for polyHEMA was $1.72 \pm 0.1 \times 10^{-11}$ m^2 s^{-1} at 37°C, which is in close agreement with the value of 1.5×10^{-11} m^2 s^{-1} interpolated from values previously reported by Gehrke et al. [16]. However, an examination of the experimental data and the fitted curve shown in Fig. 10(A) shows that there is a structure in the deviations of the experimental points about the fitted curve. These deviations are consistent with what would be expected if a discontinuity in behaviour occurred at the point where the glassy core disappears, at a mass uptake ratio of approximately 60%, as described by Gehrke et al. [16]. Therefore, a second data analysis was performed using only the mass uptake data obtained prior to the disappearance of the glassy core, as performed by Gehrke et al. [16]. This yielded a value of D of 1.56 ± 0.1 m^2 s^{-1} which is in excellent agreement with the value obtained by Gehrke et al. The values of D obtained from similar analyses of the data shown in Figs. 8 and 9 for the copolymers are summarized in Table 1 and Fig. 11(A).

With increasing proportions of BMA or CHMA in the copolymers, the diffusion coefficients decreased, reflecting the influence of the compositional microstructure of the

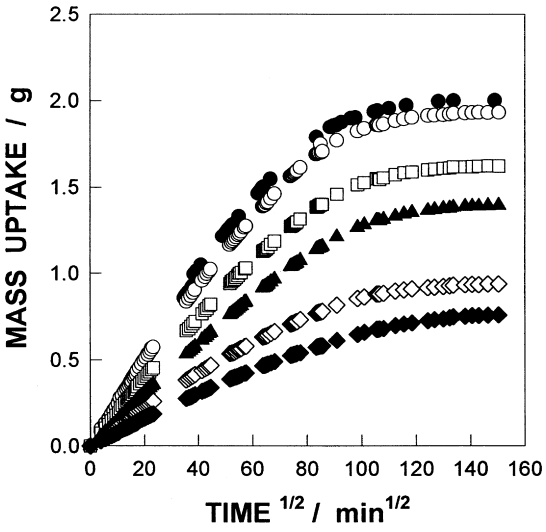

Fig. 8. Water uptake measurements for BMA/HEMA copolymers of mole fraction, F, at 37°C, $F_{BMA} = 0.0$ (●); $F_{BMA} = 0.025$ (○); $F_{BMA} = 0.05$ (□); $F_{BMA} = 0.075$ (▲); $F_{BMA} = 0.1$ (◇); and $F_{BMA} = 0.15$ (◆).

copolymers on the diffusion of water into the cylinders. As the concentration of HEMA in the copolymers decreases, the HHH triad fraction decreases, and as a result the polar HEMA groups more frequently have a non-polar BMA or CHMA neighbour. This has the effect of inhibiting the diffusion of the polar water molecules through the copolymer matrix. The incorporation of small amounts of CHMA into the HEMA copolymers was found to have a slightly greater effect on the diffusion coefficient for water than that for the incorporation of small amounts of BMA.

Franson and Peppas [18] have studied the diffusion of water into poly(methyl methacrylate-co-hydroxylethyl methacrylate), MMA/HEMA, copolymers at 37 ± 0.5°C. We have analysed their data to estimate the ratio of the

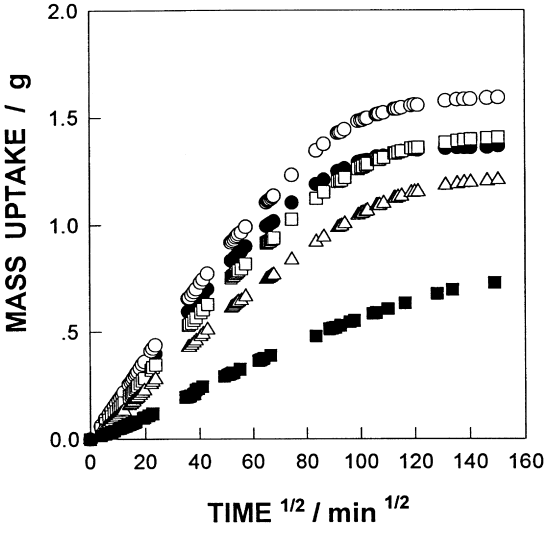

Fig. 9. Water uptake measurements for CHMA/HEMA copolymers of mole fraction, F, at 37°C, $F_{CHMA} = 0.025$ (○); $F_{CHMA} = 0.05$ (●); $F_{CHMA} = 0.075$ (□); $F_{CHMA} = 0.1$ (△); and $F_{CHMA} = 0.2$ (■).

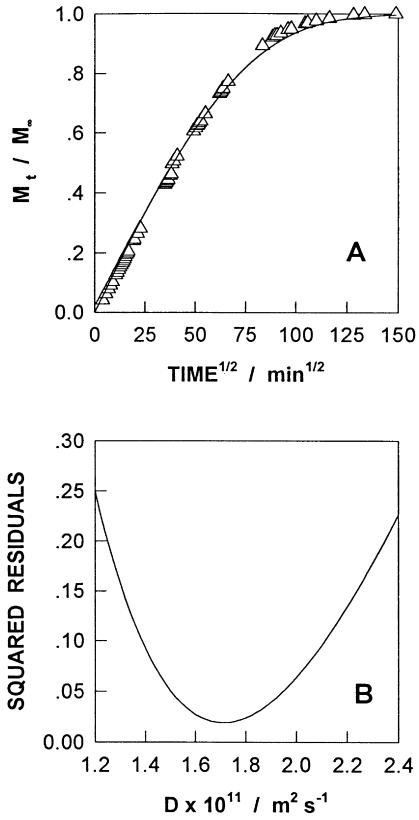

Fig. 10. The Fickian model curve fit to the relative mass uptake measurements for HEMA: (A) least squares data fit to all the relative mass uptake data; and (B) section through the hypersurface for the data fit.

diffusion coefficients for the copolymers to that for HEMA, D/D_{HEMA}, and we have compared these values in Fig. 11(A) with the corresponding values for the BMA/HEMA and CHMA/HEMA copolymers. It is apparent from the figure, that, although the data for MMA/HEMA are less reliable, the diffusion coefficients for this system are larger than the diffusion coefficients for the other two systems at comparable copolymer compositions. In addition, the data in the figure show that the diffusion coefficients deviate significantly from a linear dependence on the polymer composition for all three of the methacrylate/HEMA copolymers, but particularly for BMA/HEMA and CHMA/HEMA.

The HEMA sequence distribution would be expected to play an important role in determining the diffusion behaviour for water in the copolymers. This has been examined in Fig. 11(B), where the relationship between the diffusion coefficient and the average HEMA sequence length has been examined. The average sequence lengths for the copolymers were calculated using the terminal model reactivity ratios [8]. For the MMA/HEMA copolymers, the reactivity ratios reported by Varma and Patnaik [10] were used in the calculations. As the average HEMA sequence length increases, the diffusion coefficient for water decreases slowly until the average sequence length falls to about 50 units, then as the average HEMA sequence lengths fall

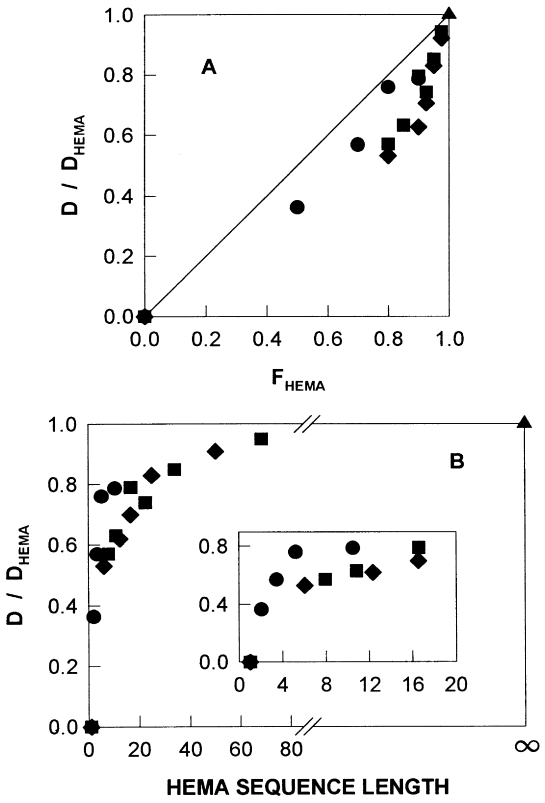

Fig. 11. The diffusion coefficient for the copolymer relative to the diffusion coefficient for HEMA, D/D_{HEMA}, for the copolymers at 37°C: (A) plotted versus the polymer mole fraction HEMA, F_{HEMA}; and (B) plotted versus the average sequence length for HEMA. BMA/HEMA (■), CHMA/HEMA (◆) and MMA/HEMA [18] (●).

below 50, the diffusion coefficient begins to fall rapidly, approaching zero as the sequence length drops to unity. A sequence of 50 HEMA units corresponds to an extended (zig-zag) segment length [12] of approximately 10 nm.

A comparison of the difference in the behaviour of the BMA and CHMA copolymers on the one hand, and the MMA copolymers on the other, shows that the diffusion coefficients of the latter polymers are larger than those of the former polymers for HEMA sequence lengths of 1–12 units.

3.8. Mass uptake of water at equilibrium

The mass fraction of water at equilibrium is an important parameter in studies of the behaviour of hydrogels. The water uptake at equilibrium expressed as a percentage of the original mass of polymer, S_∞, is

$$S_\infty = [(M_\infty - M_0)/M_0] \times 100 \quad (3)$$

where M_0 is the mass of the dry polymer cylinder at time zero and M_∞ is the mass of the polymer cylinder plus water at time infinity.

The BMA/HEMA hydrogels reached an equilibrium mass uptake within 7 days at 37°C, with S_∞ varying from 27.2 to 58.8% as the proportion of HEMA increased from $F_{HEMA} = 0.85$–1.00 in the copolymer (see Fig. 12(A)). A similar trend was observed for the CHMA/HEMA and MMA/HMA hydrogels, except that the CHMA/HEMA hydrogels absorbed water to a slightly smaller extent at a given copolymer composition (21.3% for $F_{HEMA} = 0.80$). The value of S_∞ for the MMA/HEMA hydrogels (32.0% for $F_{HEMA} = 0.8$) was greater than that for the other two series of polymers at the same copolymer composition, presumably because the comonomer in these gels has a much less bulky hydrophobic ester group.

The effect of the changes in the average HEMA sequence length on the value of S_∞ for the BMA/HEMA and CHMA/HEMA copolymers follows similar trends to those for the diffusion coefficients, see Fig. 12(B). Again, the corresponding values for the MMA/HEMA are greater than the values for the other two series, reflecting a greater extent of hydration of the HEMA units in the MMA copolymers.

4. Conclusion

The reactivity ratios for the BMA/HEMA and CHMA/HEMA copolymers were determined as $r_{HEMA} = 1.73$, $r_{BMA} = 0.65$ and $r_{HEMA} = 1.26$, $r_{CHMA} = 0.31$, respectively.

Table 1
The diffusion coefficients for water at 37°C for BMA/HEMA and CHMA/HEMA copolymers as a function of the HEMA mole fraction, F_{HEMA}, calculated for a Fickian model

F_{HEMA}	BMA/HEMA		CHMA/HEMA	
	$D \times 10^{11}$ ($m^2\ s^{-1}$)[a]	$D \times 10^{11}$ ($m^2\ s^{-1}$)[b]	$D \times 10^{11}$ ($m^2\ s^{-1}$)[a]	$D \times 10^{11}$ ($m^2\ s^{-1}$)[b]
1.000	1.72	1.56	1.72	1.56
0.975	1.62	1.49	1.58	1.41
0.950	1.46	1.34	1.43	1.30
0.925	1.28	1.16	1.21	1.07
0.900	1.37	1.31	1.08	0.94
0.850	1.09	1.02	–	–
0.800	0.97	–	0.91	0.61

[a] Determined using the mass uptake data up to the equilibrium point.
[b] Determined using the mass uptake data up to the point where the glassy core was lost.

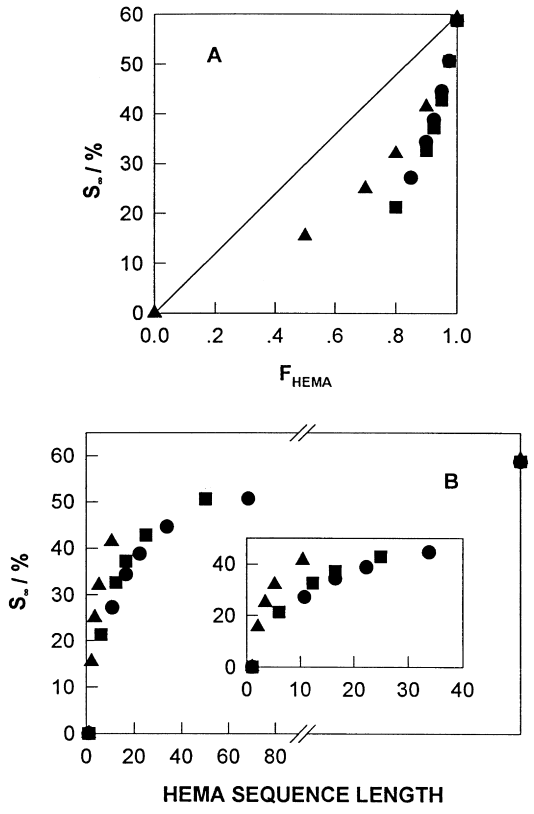

Fig. 12. Percent water absorbed at equilibrium, S_∞, for the copolymers at 37°C plotted versus: (A) the polymer mole fraction HEMA, F_{HEMA}; and (B) the average sequence length for HEMA in the copolymer. BMA/HEMA (●), CHMA/HEMA (■) and MMA/HEMA [18] (▲).

HEMA was found to be the more reactive of the two monomers in both systems, and especially in the CHMA/HEMA system. The reactivity of HEMA had a profound effect on the microstructure of both the low and high conversion polymers. By increasing the proportions of HEMA in a copolymer, the sequence distributions show that more HHH triads are formed, which are more favourable for the uptake of water. By introducing more of either the BMA or CHMA units into the copolymer, a larger proportion of BH or CH dyads are formed, which provide a barrier to the uptake and diffusion of water.

Because of the greater reactivity of HEMA in the CHMA system, the CHMA copolymers have a slightly greater tendency towards alternation. The BMA copolymers contain on average slightly longer HEMA sequences than the CHMA copolymers. The homopolymers and copolymers were shown to be highly syndiotactic, with the isotacticity parameters for the homopolymers of BMA and CHMA found to be 0.18 and 0.19, respectively.

The diffusion coefficient can be controlled by the addition of non-polar monomers to the polar HEMA monomer. By decreasing the proportion of HEMA in a copolymer, the average HEMA sequence length in the copolymer decreases. For example, the diffusion coefficient decreased significantly from $1.72 \pm 0.1 \times 10^{-11}$ m^2 s^{-1} for polyHEMA to $\approx 9.1 \pm 0.1 \times 10^{-12}$ m^2 s^{-1} for the CHMA/HEMA copolymer of composition $F_{HEMA} = 0.8$. The diffusion behaviour for water was characteristic of Fickian diffusion for both copolymer systems.

The difference in the copolymer microstructure was used to explain the observed water mass uptake behaviour of the two systems. The CHMA copolymers had a slightly greater tendency towards alternation, so the BMA copolymers have somewhat longer average HEMA sequences length for a given copolymer composition. For a particular copolymer composition, the BMA copolymers had a slightly greater mass uptake of water at equilibrium than the CHMA copolymers, and also slightly greater diffusion coefficients, which are a reflection of the differences in the HEMA sequence structure.

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