Physical properties of 2-acetoxyethyl methacrylate and 2-hydroxyethyl methacrylate copolymers

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2-Acetoxyethyl methacrylate (AcEMA) has been synthesized from 2-hydroxyethyl methacrylate (HEMA) and polymers and copolymers of the two monomers have been prepared. The effect of composition on the physical properties of the copolymers has been evaluated by d.s.c. and determination of tensile mechanical properties, both on dry and wet samples, flexural dynamic mechanical properties (d.m.t.a.) on dry samples, and water sorption and desorption kinetics. The addition of the more flexible component (AcEMA) significantly lowers the copolymer glass transition and affects its overall properties. These differences are explained by the d.m.t.a. measurements, with storage and loss moduli strongly depending on the copolymer composition. The mechanical behaviour of the copolymers ranges from glassy to rubbery, as a function of composition, with elastic moduli in the range of 100–2500 MPa for dry copolymers and 35–0.3 MPa for wet copolymers. Similarly, the equilibrium water content is affected by the balance of hydrophobic–hydrophilic monomer content, with a higher amount of water being absorbed in copolymers containing less AcEMA.

(Keywords: hydrogels; copolymers; physical characterization; poly(2-acetoxyethyl methacrylate-*co*-2-hydroxyethyl methacrylate)

INTRODUCTION

2-Hydroxyethyl methacrylate (HEMA) based polymers (P-HEMA) and copolymers have been extensively studied mainly for their applications in the biomedical field. HEMA still represents the preferred basic material for the construction of soft contact lenses[1], and is used for drug delivery systems[2] and has been proposed for other surgical applications[3].

After Wichterle and Lim, who first polymerized HEMA in the presence of a crosslinking agent and water[4], a set of P-HEMAs has been prepared by changing the initiator type and conditions, crosslinker type and amount, and polymerization media[5–10]. Starting from HEMA, a number of copolymers or blends with fewer or more hydrophilic monomers have also been investigated, with the interest mainly being in blood-contacting materials[11–13] or drug delivery systems[13–17]. In the former, a proper balance between hydrophilic and hydrophobic groups plays an important role in the antithrombogenicity of the material; in the latter, copolymerization can be used as a tool to tailor the material diffusion properties.

Okano *et al.*[18] have shown that the block copolymerization of HEMA with styrene can create a surface with microdomains having hydrophobic or hydrophilic character, resulting in an improvement of the antithrombogenic properties of pure P-HEMA. On the other hand, copolymerization of HEMA with methyl methacrylate[19] strongly affects the polymer water sorption capability as well as its water diffusion kinetics, leading to materials with a large variety of properties when wet, even if very similar when dry. Physical properties of dry P-HEMA are close to those of poly(methyl methacrylate), with a glass transition temperature (T_g) of ~100°C and a typical glassy behaviour. In the presence of water, the material swells and its T_g drops well below 0°C. Diffusion properties of P-HEMA are triggered by its glass transition, the diffusion coefficient of the glass being orders of magnitude lower than that of the rubber.

For application in the field of drug release for transdermal drug delivery systems, Verhoeven *et al.*[17] have suggested the use of polyethyleneglycol as plasticizer in order to decrease the P-HEMA transition below body temperature. In this paper, we have studied some properties of copolymers of HEMA with 2-acetoxyethyl methacrylate (AcEMA)[20], a monomer derived from HEMA through the esterification of the OH groups, with the aim to produce HEMA based materials having T_gs, and hence properties, which depend on composition, both in the dry and wet state.

EXPERIMENTAL

Synthesis of AcEMA

AcEMA has been synthesized from HEMA by esterification with acetic anhydride using perchloric acid

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as catalyst. In a Erlenmeyer flask, acetic anhydride (306 ml, 98%; Carlo Erba, Italy), with perchloric acid (0.3 ml, 65%; Carlo Erba), was added dropwise over ~2 h to HEMA (390 ml, purity 99%, stabilized with 50 ppm of methyl hydroquinone; Rohm, Germany). The reaction proceeded very quickly, as shown by the exothermicity immediately following mixing of the reagents, and was completed overnight. Then the product was purified by extraction in water (1:1 v/v), three times, followed by filtration on paper filter, twice, in order to eliminate the residual water. The AcEMA monomer was characterized by *FT*i.r. and n.m.r. spectroscopy.

Monomer characterization

The purity of the AcEMA synthesized was reported to be ~99%, as determined by gas chromatography[20]. Both monomers, liquid at room temperature, have been characterized by *FT*i.r. and ^{1}H n.m.r., in order to check the efficiency of the reaction of HEMA in AcEMA. *FT*i.r. spectra were obtained from monomer film cast onto NaCl plates using a Nicolet 600X spectrometer, and n.m.r. analysis was performed at 400 MHz using a 2–3 mg ml^{-1} deuterated chloroform solution on a Brüker 400 instrument.

Polymerization

Polymers and copolymers of HEMA and AcEMA were prepared in the form of discs in aluminium plates (100 mm diameter, 2 mm thick) by free radical polymerization with benzoyl peroxide (0.2 wt%) at 80°C for 3 h under a nitrogen atmosphere, followed by curing for 1 h at 130°C. Aluminium was chosen after other polymerization attempts, in which poly(tetrafluoroethylene) (Teflon), polyethylene or calcium monohydrogenphosphate saturated water solution were used as polymerization supports. Copolymers containing 0, 25, 50, 75 and 100 wt% AcEMA were prepared. From the discs, samples of various shapes and sizes depending on the characterization protocol used were cut and stored in a desiccator.

Thermal analysis

Differential thermal analysis was performed in a Mettler DSC 30 calorimeter, assisted by a computer. Samples weighing ~15 mg were used, and were heated at 10°C min^{-1} from −50 to 200°C. From the curves, completion of the polymerization reaction was confirmed in order to establish the polymerization protocol. The T_g was calculated as the temperature of the inflection point.

D.m.t.a. analysis

D.m.t.a. was performed by bending (sample size $20 \times 10 \times 2$ mm^3) in single cantilever mode, at a frequency of 1 Hz with 40 μm deformation, from −50 to 150°C for dry samples and from −100 to 100°C for wet samples at a heating rate of 2°C min^{-1} using a DMTA MkII instrument (Polymer Laboratories, UK). Care was taken in reducing any water loss from the wet samples during the clamping set-up carried out at low temperature (below 0°C). However, by the end of the experiment, samples showed the loss of a considerable amount of water. This was neglected however, since interest was focused on the behaviour of materials at temperatures at which the water loss could be assumed to be insignificant.

Mechanical properties

Mechanical properties of polymers and copolymers were measured in tension, at room temperature (~23°C), on both dry and wet samples ($80 \times 10 \times 2$ mm^3), with a crosshead rate of 1 mm min^{-1}, using an Instron 4502 dynamometer. Wet samples were maintained in air during the test, with the test being completed as quickly as possible.

Water sorption kinetics

Water sorption kinetics were measured by following the weight of three samples, previously washed in water and then dried, kept in water at 37°C until constant weight was attained.

RESULTS AND DISCUSSION

The reaction was controlled by comparing the *FT*i.r. and ^{1}H n.m.r. spectra of the original HEMA, and those of the synthesized AcEMA, as shown in *Figures 1* and *2*, respectively. The *FT*i.r. spectrum of HEMA in *Figure 1a* shows the conjugated carbonyl absorption with a typical sharp peak at 1720 cm^{-1}, and a broad peak in the range 3200–3600 cm^{-1} due to hydroxylic group stretching. The presence of a further peak at 1740 cm^{-1} in the unconjugated carbonyl zone and the disappearance of the OH peaks indicates the effective insertion of a second ester group by the acetylation reaction, as shown in *Figure 1b* for AcEMA.

Perfect agreement has been found between the n.m.r. spectra reported in *Figure 2* and the data are given in

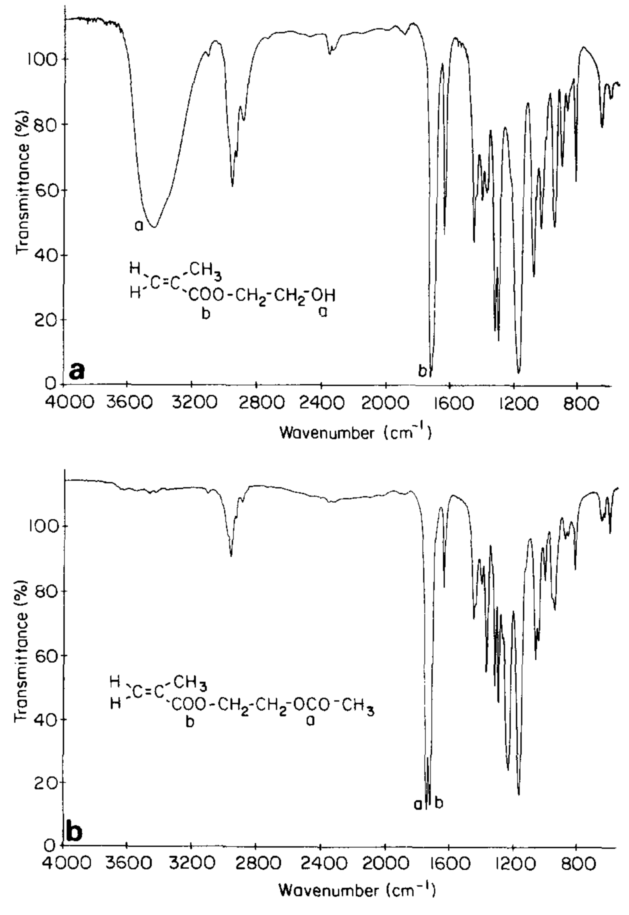

Figure 1 *FT*i.r. (NaCl discs) spectra of (a) HEMA and (b) AcEMA monomers

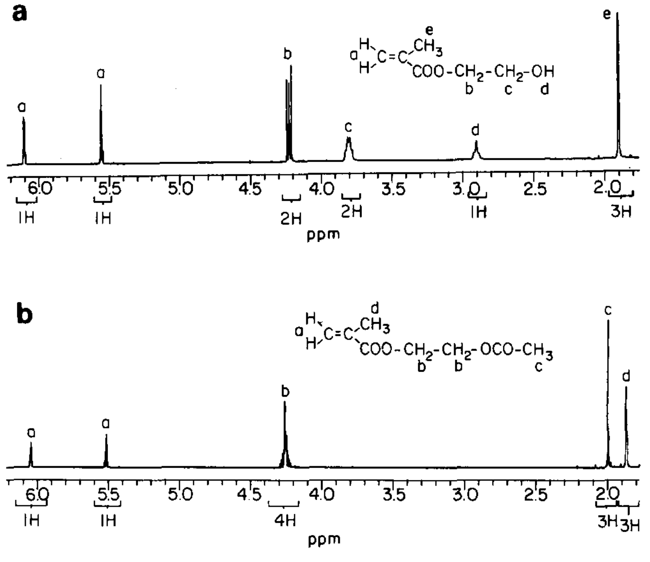

Figure 2 ^{1}H n.m.r. ($CDCl_3$ solution) spectra of (a) HEMA and (b) AcEMA monomers

Table 1. The HEMA spectrum consists of six multiplets easily assignable to the methylic (3H, 1.9 ppm), hydroxylic (1H, 2.9), methylenic (2H, 3.8 ppm and 2H, 4.25 ppm) and vinyl (1H, 5.6 ppm and 1H, 6.1 ppm) hydrogens as shown in *Figure 2a*. The acetylation reaction simplifies the spectrum of AcEMA reported in *Figure 2b*, in which the hydroxylic peak has been substituted by a singlet signal (3H, 2.0 ppm) due to the uncoupled hydrogens of the acetylic group, and the methylenic hydrogens have become equivalent (4H, 4.25 ppm) with a very low coupling constant.

The d.s.c. thermograms of HEMA-AcEMA copolymers (not shown) mostly revealed a unique homogeneous glass transition region: samples displaying two distinct glass transitions, obtained in some cases, were discarded.

The copolymerization of HEMA with the more flexible component (AcEMA) significantly lowers the glass transition and affects its overall properties. The T_g values, calculated using the above curves corresponding to the inflection point of the transition, or by d.m.t.a. analysis, as the temperature of the maximum of the loss modulus (E'') value, are reported in *Table 2*. Both sets of data compare well with the T_gs predicted by a mixture rule which relates the T_gs of the copolymers to those of the pure polymers through the monomer volume fraction, ϕ, of the two monomers:

$$T_g = T_{g_1}\phi_1 + T_{g_2}\phi_2 \qquad (1)$$

Table 2 Comparison between the T_gs of dry copolymers, as measured by d.s.c. (inflection point) and d.m.t.a. (maximum of the E'' curve), and as calculated by a mixture rule

Material (wt% AcEMA)	D.s.c. (°C)	T_g calc. (°C)^a	D.m.t.a. (°C)	T_g calc. (°C)^a
100	23.6	–	19.9	–
75	43.7	42.2	37.8	35.3
50	57.6	60.8	51.1	51.7
25	78.0	79.3	67.8	68.0
0	97.9	–	84.4	–

$^aT_g = T_{g_1}\phi_1 + T_{g_2}\phi_2$

The different T_gs affect the copolymer mechanical spectra, as is evident in the d.m.t.a. results for the storage (E') and E'' moduli and the damping factor (tan δ), respectively (*Figure 3*). At very low temperatures, the addition of AcEMA does not appreciably modify the dynamic mechanical parameters of the copolymers, which approach a comparable limiting value, as a consequence of the fact that P-HEMA and P-AcEMA have the same skeletal backbone. At higher temperatures, due to the substitution of the hydroxylic with the acetoxy group, which reduces or eliminates the possibility of hydrogen bond formation, the overall mobility of the copolymers containing AcEMA increases, as already shown by the decrease in T_g as the AcEMA content increases (see *Table 2*).

In the tan δ and E'' curves various transition peaks can be detected in the swollen samples (*Figure 4*) with a more complex pattern which overcomes melting and the transition processes[17,21,22]. The tan δ curves of the swollen samples account for the different plasticization effect by water on the copolymers. The higher the AcEMA content, the lower the water content and hence, the decrease in T_g of wet copolymers. The peak of tan δ at ~0°C in the pure P-HEMA curves is not associated with the polymer glass transition, but is due to the sudden melting of the water frozen into the materials when its temperature passes through 0°C. The other shorter and broader peak, set at ~0°C, which can be observed in the tan δ and E'' curves for the pure P-HEMA, should represent the glass transition of the polymer with only a small amount of water in a liquid-like state, with most of the water being frozen during the cooling at −100°C. In the literature[23] the glass transition of the water swollen P-HEMA is reported to be −50°C.

The temperatures corresponding to the maximum of the tan δ peak are reported in *Table 3* for the dry and wet samples, together with the amount of absorbed

Table 1 ^{1}H n.m.r. data of HEMA and AcEMA monomers

HEMA				AcEMA			
δ (ppm)	Multiplicity	Protons	Integration	δ (ppm)	Multiplicity	Protons	Integration
1.9	m	3H	2.91	1.9	m	3H	2.92
–	–	–	–	2.0	s	3H	2.89
2.9	t	1H	1.01	–	–	–	–
3.8	q	2H	2.05	–	–	–	–
4.2	m	2H	2.03	4.25	m	4H	4.03
5.05	m	1H	1.01	5.0	m	1H	1.02
6.1	m	1H	1.00	6.05	m	1H	1.00

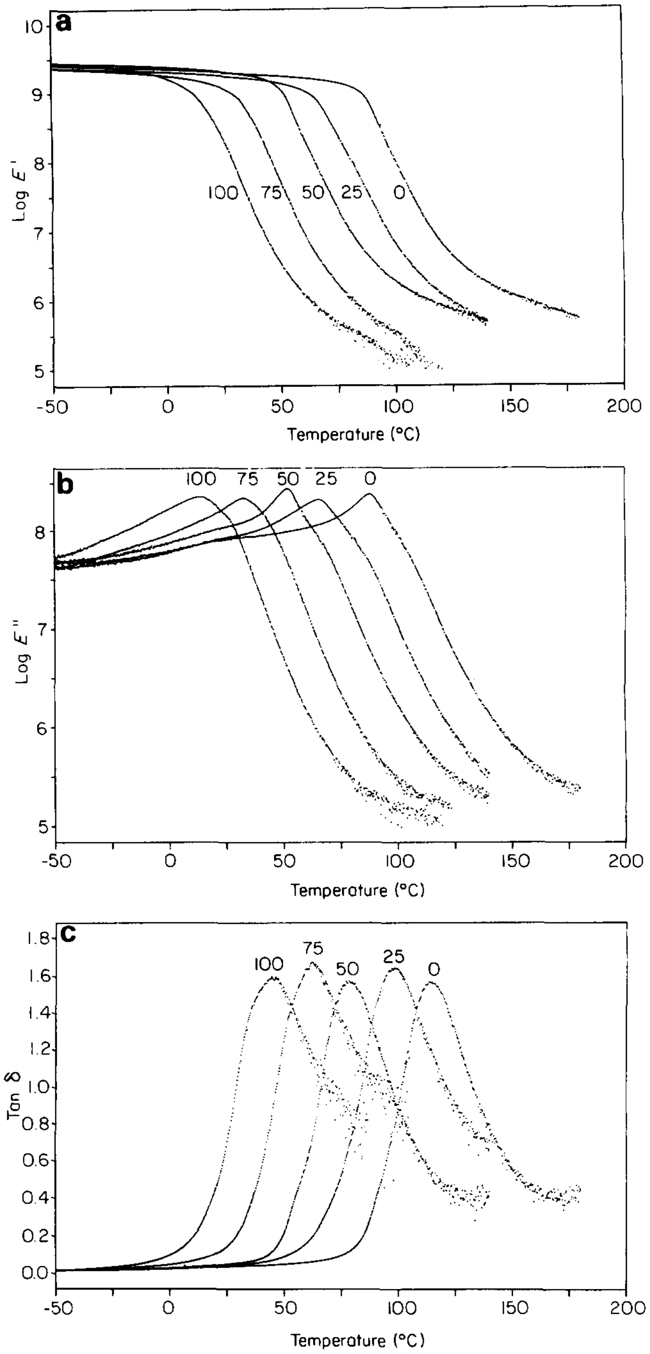

Figure 3 (a) Storage modulus (E'), (b) loss modulus (E'') and (c) damping factor ($\tan\delta$) of dry HEMA–AcEMA copolymers containing 0, 25, 50, 75 and 100 wt% AcEMA

equilibrium water. The decrease of T_g for the wet samples, i.e. the T_g of the dry sample minus the T_g of the wet sample, is strictly dependent on the percentage of water as reported in *Figure 5*. Experimental data are well fitted by a linear correlation which assumes that the plasticization effect of water is directly related to its molar or weight percentage, independent of copolymer composition. Mechanical properties of copolymers are strongly affected by the presence of water, as shown by the measured values of the elastic moduli.

Depending on composition, the copolymers display rubbery or glassy behaviour, with elastic moduli in the range of 100–2500 MPa, going from pure P-AcEMA to pure P-HEMA, as an effect of the increase of the T_g of the material (*Figure 6a*). Similarly, the equilibrium water

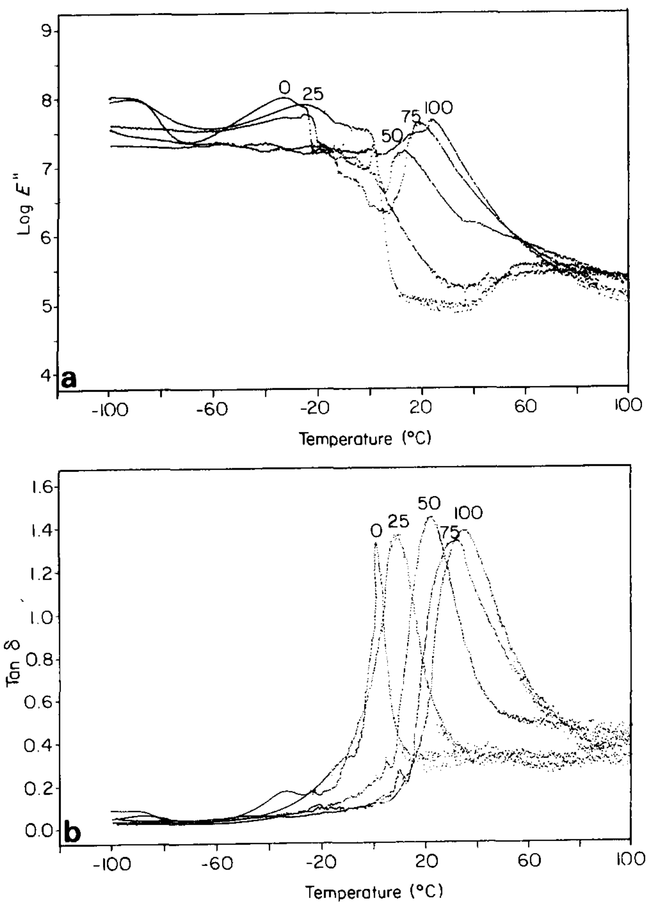

Figure 4 (a) Loss modulus (E'') and (b) damping factor ($\tan\delta$) of wet HEMA–AcEMA copolymers containing 0, 25, 50, 75 and 100 wt% AcEMA

content is affected by the balance of hydrophobic–hydrophilic groups present in the copolymers, with a higher amount of water being absorbed in the copolymers containing less AcEMA, as shown in *Table 3*.

The elastic moduli of the water swollen samples depend on the combined effect of both flexibility and hydrophilicity, with much less appreciable differences among different materials (35–0.3 MPa), as shown in *Figure 6b*. In fact, plasticization by water makes the wet copolymers much more similar than the dry copolymers, with respect to their elastic properties, as a result of the higher amount of water sorbed by the copolymers with higher HEMA content, which display in the dry state a greater stiffness.

The water sorption kinetics curves of the copolymers are reported in *Figure 7* as M_t/M_{inf} *versus* $t^{1/2}/L$, where M_t represents the water content weight at time t, M_{inf} is the equilibrium water content weight, t is the time and L is the thickness of the initial dry sample. The almost linear initial dependence indicates that the diffusion process is of Fickian type. The initial slope of the curve is proportional to the water diffusion coefficient (D), which is reported in *Table 4*, as calculated using[24]:

$$M_t/M_{\text{inf}} = (4/\pi^{1/2})(Dt/L^2)^{1/2} \quad (2)$$

The above data indicate that D increases with increasing HEMA content as reported in a previous paper[9]. The P-AcEMA exhibits an 'anomalous' D value, higher for the copolymer containing 25% HEMA. This fact depends on the two-fold effect of both hydrophilicity and glass

Table 3 T_gs measured as a maximum of the tan δ curve for dry and wet AcEMA copolymers, difference between the T_gs in the two states, and weight and mole percentage of absorbed water, both referring to the dry material

Material (wt% AcEMA)	T_g (dry) (°C)	T_g (wet) (°C)	T_g (dry)–T_g (wet) (°C)	Water (wt%/wt%)	Water (mol%/mol%)
100	46.4	38.5	7.9	3.10	29.62
75	64.7	34.2	30.5	9.41	83.21
50	82.6	24.6	58.1	19.18	157.80
25	100.2	10.8	89.4	34.89	268.76
0	116.1	−33.1	149.2	62.99	454.94

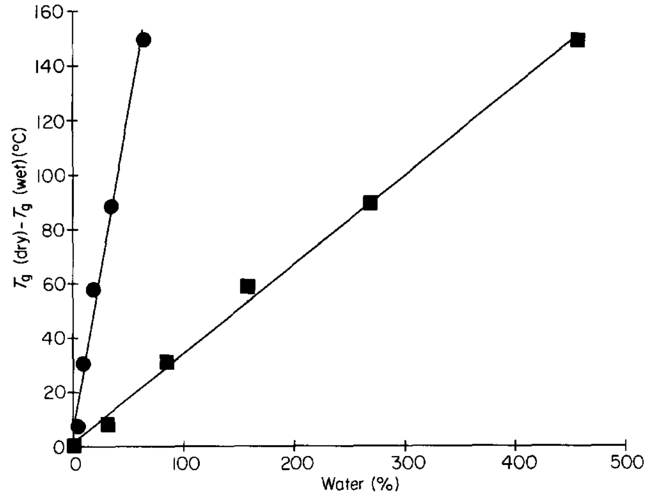

Figure 5 Effect of the equilibrium water content on the difference between the T_gs of dry and wet AcEMA–HEMA copolymers, as calculated from the damping factor curves. The equilibrium water content is expressed as a weight percentage (●) or mole percentage (■), both referring to the dry sample

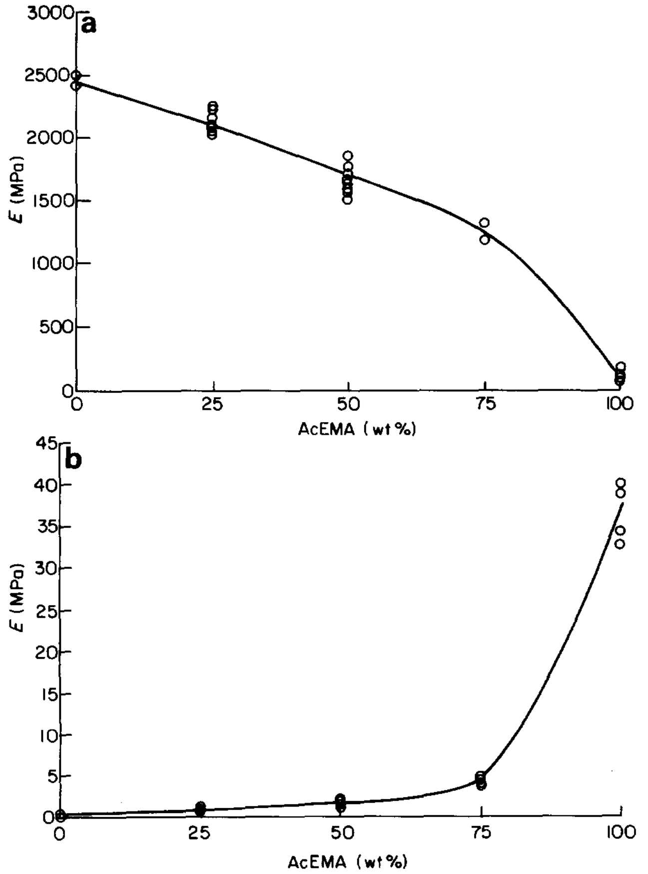

Figure 6 Tensile elastic modulus (E) of (a) dry and (b) wet copolymers

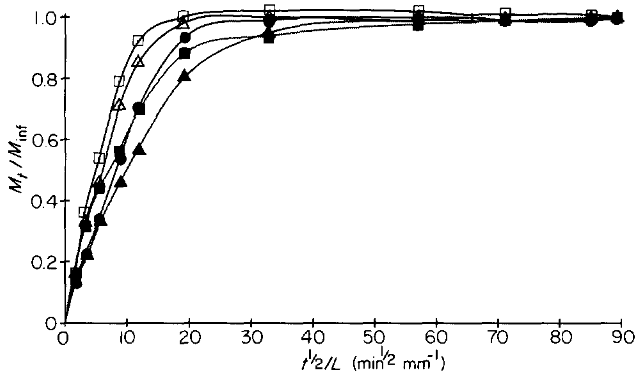

Figure 7 Water sorption kinetics of HEMA–AcEMA copolymers containing 0 (□), 25 (△), 50 (●), 75 (▲) and 100 (■) wt% AcEMA

Table 4 Equilibrium water content of copolymers expressed as weight per cent referred to the total weight of dry or swollen samples, and diffusion coefficients (D)

AcEMA (wt%)	M_t (dry)	M_t (wet)	D ($\times 10^7$) (cm^2 s^{-1})
100	3.10	2.90	0.59
75	9.41	8.77	0.44
50	191.8	16.19	1.22
25	34.89	25.95	1.28
0	62.99	38.58	1.85

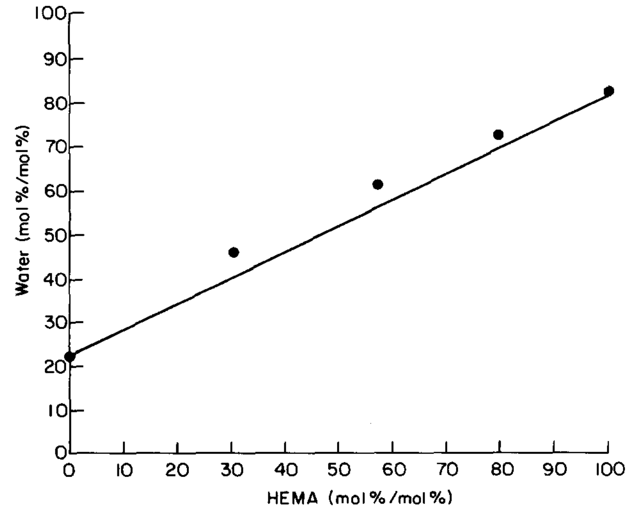

Figure 8 Equilibrium water content of copolymers *versus* HEMA molar fraction. The solid line represents the prediction made assuming a linear dependence of the water content on the HEMA molar fraction

transition on the role of water sorption. While the equilibrium water content depends on the nature and amount of hydrophilic groups of the molecules, the kinetics of the process is also affected by the material state, i.e. glassy or rubbery. The fact is well evident in the above calculated D values, where the rubbery nature of AcEMA at the temperature of the experiment (37°C) prevails on the hydrophilic nature of HEMA, up to a certain composition.

The equilibrium water content expressed as a molar fraction referred to the dry copolymers has been plotted in *Figure 8 versus* the HEMA molar fraction of dry copolymers. The experimental points for the copolymers containing 25, 50 and 75 wt% AcEMA are higher than the prediction made assuming a linear dependence of the water sorbed on the pure homopolymer data. A coupled effect of the different chemical groups present in the two monomers, i.e. the hydroxy group as hydrogen donor and the ester group as hydrogen acceptor, can be assumed to be an explanation for these phenomena.

CONCLUSIONS

Copolymerization of HEMA with AcEMA results in materials having a large variety of properties. The substitution of the OH group of HEMA with the acetoxy group eliminates the possibility of the formation of hydrogen bonds, thus affecting both the material hydrophilicity and the resulting polymer rigidity. P-AcEMA is substantially rubbery (or, better, leathery), and hydrophobic, with a T_g at ~46°C (as measured by the maximum of the damping factor curve, but lower, i.e. ~23°C, if measured by d.s.c.), when dry, and at ~38°C, if wet. The absorption of water, instead, completely reverses the glassy character of P-HEMA, and produces a material with a very low T_g and well defined rubbery behaviour. Copolymerization generates a class of materials that, in the dry state, possess mechanical properties and T_gs which decrease with increasing AcEMA content going from the pure P-HEMA to the pure P-AcEMA. The higher the AcEMA content, however, the lower the material capability to absorb water and, hence, the smaller the copolymer plasticization. Swollen copolymers, in fact, display properties which are conversely affected by the AcEMA content, and decrease as the amount of HEMA increases.

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