pH-Responsive Permeability of PE-*g*-PMAA Membranes

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ABSTRACT: Poly(methacrylic acid) (PMAA) grafted porous PE membranes (PE-*g*-PMAA) were studied. It was found that (1) a wide range of graft yields can be achieved by varying irradiation time (20–240 min) and monomer concentration (0.22*M*–0.66*M*), (2) the grafted membrane exhibits reversible permeability response, (3) the membrane shows a maximum permeability response at an intermediate permeant molecular weight due to size exclusion effect, and (4) depending on the graft yield, two types of permeability response can be obtained. These observations are consistent with our earlier study on poly(*N*-isopropylacrylamide) (PNIPAAm)–grafted porous polyethylene membranes. In addition, it was observed that the solvent used during grafting may influence the graft location—presumably due to variations in pore wetting. Specifically, compared to water solvent, methanol can increase grafting inside membrane pores, an observation inferred from membrane swelling, thickness measurement, and SEM characterization. Moreover, preferential grafting inside the membrane pores, as affected by increasing methanol content in the grafting solvent, results in lower membrane permeability and a greater pore graft-controlled type of permeability response. © 2000 John Wiley & Sons, Inc. J Appl Polym Sci 76: 778–786, 2000

Key words: responsive membranes; grafted polymers; permeability response

INTRODUCTION

Polymeric membranes that undergo property changes in response to the environment have been drawing much attention for the past decade.[1,2] Various such membranes have been prepared using different methods.[2] This article deals with porous substrate membranes grafted with responsive polymers. It is believed that the substrate will provide mechanical strength and dimensional stability, while the graft polymer provides the responsive characteristic—altering its conformation and physical structure as the environmental conditions vary. Another advantage may be the faster conformational changes expected in grafted membranes,[3] since grafted chains should have freely mobile ends while crosslinked hydrogel networks give rise to relatively immobile chain segments. This type of membrane has potential applications in drug delivery, tissue engineering, and membrane separation.[4–6] For drug delivery applications, the membrane permeability response is of particular interest. A great deal of work has been reported on this type of membrane, including different grafting methods, responsive polymers, and membrane substrates as well as the effects of graft amount and permeant size on the permeability response. However, graft location and its effect on permeability response have not been well investigated.

In a previous study on poly(*N*-isopropylacrylamide) (PNIPAAm)–grafted PE porous membranes,[7] we reported that the graft polymer may be positioned either primarily inside the membrane pores or on the external surface of the membrane and that two types of temperature-responsive permeability may be observed depend-

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ing on the graft yield and location. With these observations in mind, PE-*g*-PMAA porous membranes with a wide range of graft yields were prepared by UV irradiation. Methanol–water mixtures of varying composition were used as the solvents in the photografting procedure to control graft location and thus the permeability response. Photografted membranes were characterized by SEM, swelling, and thickness measurements. The pH-dependent permeability response of the grafted membranes was studied as a function of the graft yield and permeant molecular weight. Dynamic permeability response to alternating pH changes was investigated as well.

EXPERIMENTAL

Materials

Low-density polyethylene (PE) porous membranes produced by thermally induced phase separation were a gift from 3M Company (Minneapolis, MN). The PE membrane is a flat sheet with 50.5 μm thickness, 70.5% porosity, and an average pore diameter of 0.19 μm as specified by the manufacturer. Methacrylic acid (MAA) monomer, purchased from Polyscience Co. (Warrington, PA), was purified by distillation under vacuum, and photoinitiator xanthone, purchased from Aldrich Co. (Oakville, ON, Canada), was used as received.

Photografting

The grafting process is as follows: 7 cm × 10.5 cm rectangular PE substrate membranes were washed by acetone extraction for 24 h, vacuum dried at room temperature, and weighed. The membrane was then soaked in an acetone solution containing 0.3 wt % xanthone for 24 h, removed from solution, and dried under vacuum at room temperature to prepare a xanthone-adsorbed film. Then 135 mL of MAA solution in deionized water or methanol–water mixtures in concentrations between 0.22*M* and 0.66*M* was introduced into the reactor and purged with nitrogen for 20 min. The xanthone-adsorbed polyethylene film was fixed on the surface of the reactor's inner tube and was then immersed in the monomer solution. The graft polymerization was initiated by UV irradiation provided by a Rayonet photochemical minireactor Model RMR-600 (Southern New England Ultraviolet, Branford, CT). Reaction then proceeded under a nitrogen atmosphere for specified amounts of time ranging from 20 to 240 min. The reacted membrane was washed with 60°C water for 24 h and then dried under vacuum. The washing procedure was repeated until a stable dry membrane weight was obtained. Graft yield was then calculated as $(W_g - W_u)/W_u$, where W_u and W_g are the dry weights of the ungrafted and grafted membrane, respectively.

Characterization: Membrane Swelling, Thickness, and SEM

To determine membrane swelling and thickness, a membrane was placed in various pH buffer solutions with an ionic strength of 0.01*M* at 37°C. At specified time intervals, the membrane was removed, and excess surface water was eliminated with Kimwipes. Membrane weight and thickness were measured by a balance with an accuracy of 0.0001 g and a micrometer with an accuracy of 0.01 mm, respectively. The procedure was repeated until equilibration. The equilibrium swelling ratio was calculated as $(W_s - W_g)/W_g$, where W_g and W_s are the weights of the dry grafted membrane and the swollen membrane, respectively. The relative membrane thickness is calculated as the ratio of the thickness at pH 7.4 ± 0.05 relative to that at pH 4.4 ± 0.05.

The morphology of the membrane cross sections was visualized by a scanning electron microscope (Hitachi X650). Samples were first freeze-fractured under liquid nitrogen and mounted on a SEM stub with glue. Carbon paint was used to connect the samples with the stub. All the samples were then vapor-coated with gold in a sputter coating system.

Permeability Measurement

Permeation experiments were carried out using standard side-by-side diffusion cells. The grafted membranes were cut into discs and placed first in methanol to wet the pores of the membrane, then in a pH 7.4 ± 0.05 phosphate buffer with an ionic strength of 0.01*M*. Each membrane was then immersed in buffer solutions with an ionic strength of 0.01*M* and different pHs at 37°C for more than 24 h prior to initiating permeation experiments. After checking for leakage, 25 mL of buffer solution with an ionic strength of 0.01*M* and permeant solution in the same buffer were added simultaneously to the receptor and acceptor cells, respectively, and stirred with a pair of magnetic bars. Then 0.2 mL solution was removed from the receptor cell at periodic time intervals, and solute concentration was determined by UV (Hewlett-Packard 8452Win Diode-array UV spectrophotometer). The sample was replaced with 0.2 mL blank buffer. Permeability was calculated using

$$\ln(1-2C_r/C_0) = -2PAt/(LV)$$

where C_r is the concentration in the receptor cell at time t and C_0, P, A, L, and V are the initial solute concentrations in the donor compartment, permeability, effective diffusion area, thickness of the membrane in the buffer, and volume of the receptor compartment. The permeability coefficient, P, can be calculated from the slope of the straight line obtained by plotting $\ln(1-2C_r/C_0)$ versus t. The swollen membrane thickness was used in this calculation to account for the significant changes in membrane thickness with solution pH. Dynamic permeation experiments were conducted by changing the buffer pH of the permeant solution and receptor buffer in each permeation cell.

RESULTS AND DISCUSSION

Photochemical Grafting of MAA onto Porous PE

Photografting of MAA onto PE membranes was investigated, and the effects of various graft conditions on graft yield are shown in Figure 1. As seen in Figure 1(a), graft yield increased with increasing monomer concentration for grafting using MAA dissolved in water or a 1 : 3 water–methanol solvent. Figure 1(b) shows that graft yield increased with UV irradiation time. Moreover, within the range of irradiation times investigated, graft yield increased linearly with time for all grafting solutions tested. Graft yield increases may be ascribed to either increasing chain length or increasing density of the graft polymer. Further investigations beyond the scope of this study are required to distinguish between these two possibilities and to explain the effects of the monomer concentration and UV irradiation time on the graft yield.

Figure 1(c) shows the effect of solvent composition on graft yield. A maximum in graft yield versus volume fraction methanol was observed. At low methanol volume fractions, increasing methanol content promotes grafting and increases graft yield. A possible explanation is that methanol–water mixtures wet the pores of the hydrophobic PE membranes more readily than pure water, thus facilitating contact between MAA monomers and the pore surfaces. This would result in increased polymer grafting inside the membrane pore. Supporting evidence for solvent-influenced graft location based on swelling, thickness, and SEM characterization are discussed below. In contrast, at higher methanol volume fractions, further increases in the methanol content of the grafting solvent resulted in decreases in graft yield. Since the solubility of the photoinitiator xanthone in methanol–water increases with methanol content [solubility in 50% methanol (0.21 mg/mL)] is more than 40 times higher than that in water (<0.005 mg/mL), it is plausible that solvents of higher methanol content may dissolve and remove the PE-adsorbed photoinitiator, leading to a reduction in graft polymerization.

In summary, PE-*g*-PMAA porous membranes with a wide range of graft yields were prepared by varying monomer concentration and irradiation time using different grafting solvents.

Membrane Characterization: Graft Location and Morphology

Figure 2 shows the effect of graft yield and pH on membrane swelling for graft membranes prepared in either water or a 50:50 mixture of methanol : water. Swelling experiments were conducted in pH 4.4 or pH 7.4 buffer solutions, below and above the pK_a of PMAA. It can be seen that swelling increases with graft yield. In addition, at pH 7.4, when the grafted PMAA chains are in the expanded state, the effect of graft yield on swelling is more pronounced than at pH 4.4, when the PMAA chains are in the collapsed state. Moreover, membranes grafted in water exhibit much larger swelling ratios than those prepared in methanol–water. From this, it can be assumed that additional grafted polymers are located inside the pores of the membrane prepared in methanol–water since the polymer chains grafted on the external surface would swell with less restriction than those inside the membrane pores, which would become more significant with increasing graft yield.[8,9]

The effect of graft yield and solution pH on the dimensions of the membrane is shown in Figure 3. The relative thickness (thickness at pH 7.4/thickness at pH 4.4) increases with increasing

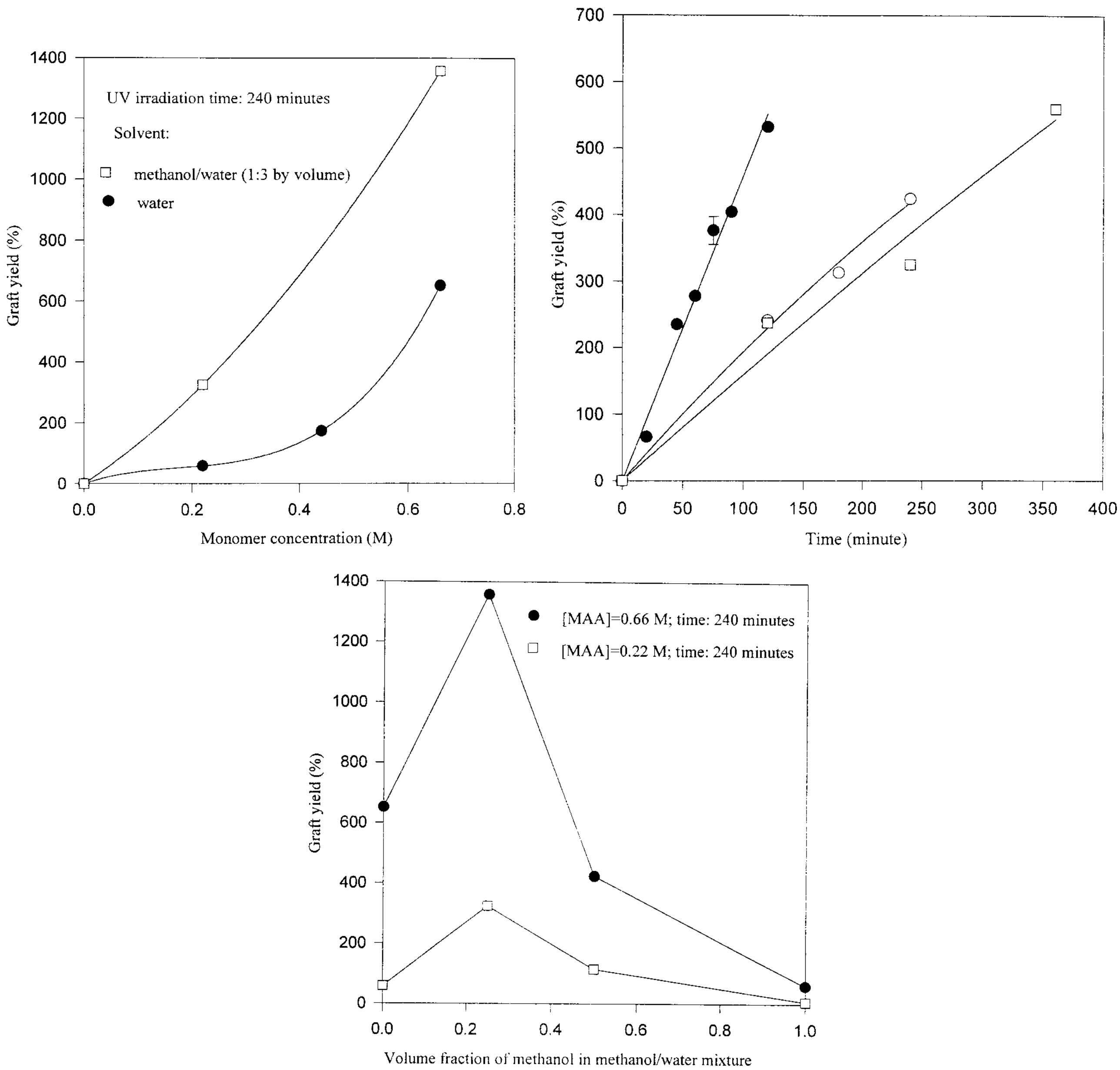

Figure 1 (a) Effect of monomer concentration on graft yield. (b) Effect of UV irradiation time on graft yield: (●) grafted in water, [*MAA*] = 0.66*M*; (○) grafted in methanol–water (1 : 1 by volume), [*MAA*] = 0.66*M*; (□) grafted in methanol–water (1 : 3 by volume), [*MAA*] = 0.22*M*. (c) Effect of grafting solvent composition on graft yield.

graft yield, as expected. In addition, membranes grafted in water show more pronounced pH-responsive changes in thickness than membranes prepared in methanol–water. Since graft polymers on the external membrane surface are expected to have greater impact on the overall membrane thickness than those inside the membrane pores, these results suggest polymers were grafted inside the membrane when methanol–water was used as the grafting solvent instead of water.

The graft location can be further confirmed by SEM pictures of the membrane cross section. Figure 4 shows that grafted membranes [Fig. 4(b,c)] are thicker than the nascent substrate [Fig. 4(a)]; this observation can be attributed to the presence of graft polymers on the external membrane surface. In addition, it appears that the membrane

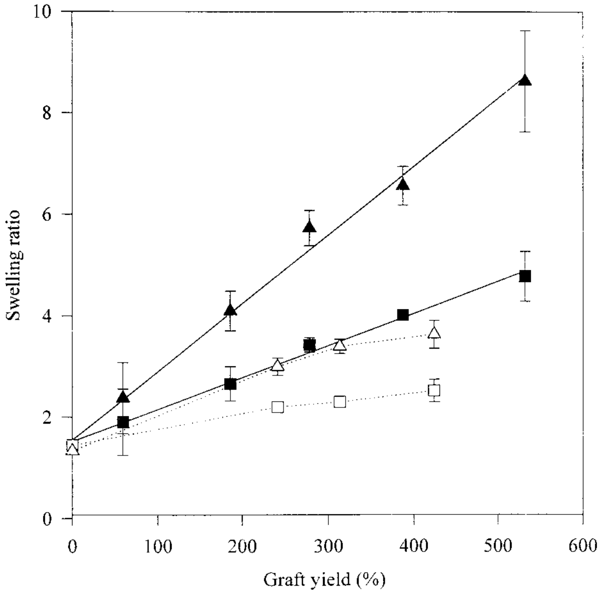

Figure 2 (a) Effect of the graft yield on swelling ratio from different solvents and pHs: ▲ (water, pH 7.4), ■ (water, pH 4.4), △ (1 : 1 methanol–water, pH 7.4), □ (1 : 1 methanol–water, pH 4.4) Error bars are standard deviation ($n = 3$).

grafted in methanol–water [Fig. 4(c)] is thinner and shows a higher-density bulk region than the membrane grafted in water [Fig. 4(b)]. These observations are consistent with the swelling and thickness results presented earlier that indicated methanol–water promotes PMAA grafting inside the pores.

Permeation Study

Effect of Grafting Solvent

In the above discussion it has been shown that increasing the methanol content of methanol–water mixtures used in photografting solvent results in preferential grafting of PMAA in the membrane pores. Figure 5 shows the permeability of vitamin B_{12} at pH 7.4 through membranes grafted from methanol–water mixtures of varying methanol content. As the graft yield increases, it can be seen that permeability initially decreases for all grafting solvents and then increases with further increases in the graft yield. This observation can be explained by viewing the membrane as a composite of two layers: a porous membrane layer and a surface graft layer that behaves similar to a hydrogel membrane. At low graft yields, the porous membrane layer dominates, and any graft polymer in the pores reduces the effective pore size, resulting in decreased overall permeability. Further increases in graft yield give rise to a more prominent surface graft layer, and the higher permeability of the surface layer relative to the porous membrane layer results in a higher overall membrane permeability—calculated using the swollen thickness of the entire membrane. It has been reported that the swelling of surface-grafted poly(4-vinylpyridine) on a porous polypropylene microfiltration membrane would result in an increase of its overall hydration, which becomes more significant with increasing graft yield.[10]

Figure 5 also shows that membrane permeability decreases with increasing methanol content in the grafting solvent. Using the two-layer composite picture again, the preferential grafting in the pores as methanol content increases results in reduced permeability of the porous membrane layer, thus giving rise to reduced overall permeability. In addition, Figure 5 indicates that the graft yield at which minimum permeability is observed is higher for membranes grafted in mixtures of water and methanol than it is only in water.

Effect of Solution pH and Graft Location

The pH-dependent permeability of vitamin B_{12} through PE-*g*-PMAA with a wide range of graft

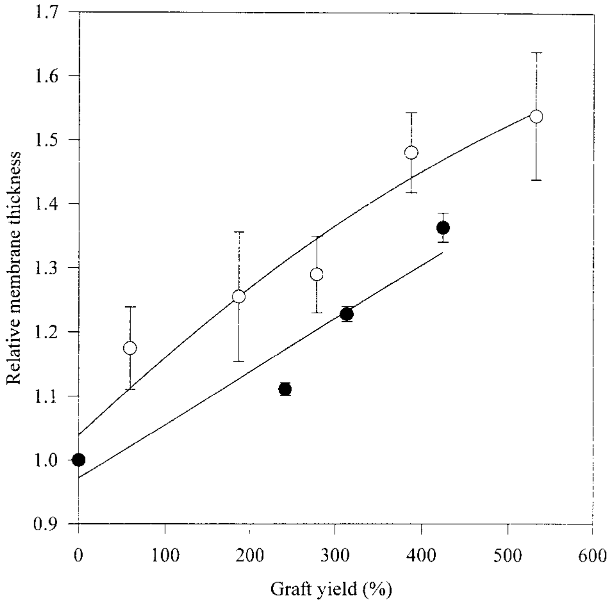

Figure 3 Thickness changes of the membrane grafted in water (○) or methanol–water with volume ratio of 1 (●) in response to pH changes between pH 4.4 and 7.4 as a function of the graft yield. Error bars are standard deviation ($n = 4$).

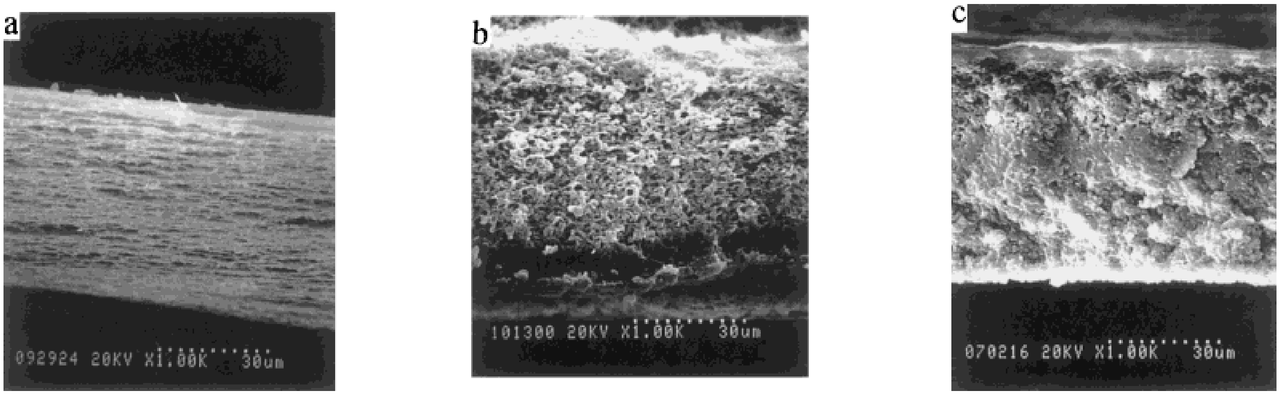

Figure 4 SEM of membrane cross sections: (a) ungrafted; (b) membrane grafted in water with 278% graft yield; (c) membrane grafted in methanol/water (1 : 1) with 313% graft yield.

yields is shown in Figure 6. There are two types of permeability response depending on the graft yield. At low graft yields, the membrane shows porous membrane responsive behavior, that is, the collapse of the graft polymer would leave the membrane pore open compared with the expansion of the polymer. At high graft yields, the membrane becomes a hydrogel-like membrane showing lower permeability in the collapsed state.

Figure 7 shows the effect of graft location on the permeability response—described as the ratio of the permeabilities in pH 4.4 and 7.4. It can be seen that compared with water as a grafting solvent, a methanol–water solvent promotes the membrane response as a polymer-grafted porous membrane where a "through-pore mechanism"[11] is observed. In addition, the methanol–water grafted membrane may show the hydrogel type of permeability response at a higher graft yield due to solvent reducing the formation of the hydrogel layer, especially for methanol–water solvent with 1 : 1 volume ratio. The result is consistent with those shown in Figures 5 and 6 and can be ex-

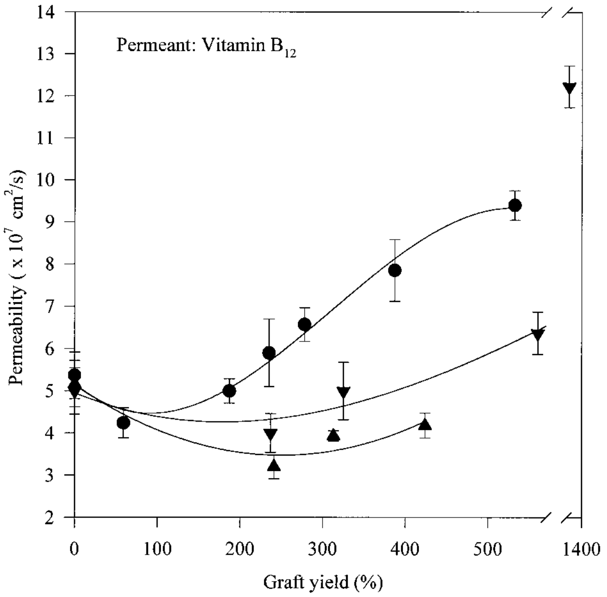

Figure 5 Permeability of the PE-*g*-PMAA membrane prepared in water (●) and methanol–water (1 : 3 by volume: ▼ or 1 : 1 by volume: ▲) as a function of the graft yield in pH 7.4 buffer solution. Error bars are standard deviation ($n = 3$).

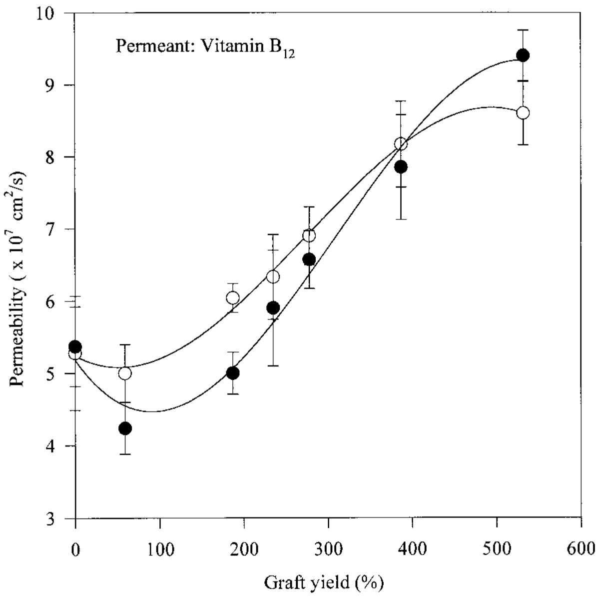

Figure 6 Permeability of the PE-*g*-PMAA membrane prepared in water with different graft yields in pH 4.4 (○) and pH 7.4 (●) buffer solution. Error bars are standard deviation ($n = 3$).

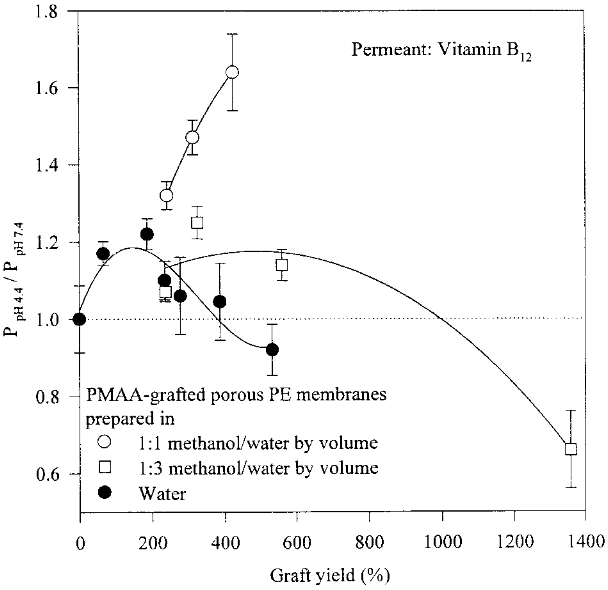

Figure 7 Effect of grafting solvent on the permeability response. Error bars are standard deviation ($n = 3$).

plained as follow: with more and more grafts on the external membrane surface, a hydrogel layer would form on the porous substrate, switching the porous membrane responsive behavior to the hydrogel responsive behavior. In contrast, for the membrane with the polymer inside the pores, the membrane permeability would be regulated by the conformation change of all the grafts inside the pores. Even at high graft yields, the formation of the hydrogel layer is prevented from reducing the valve function of the grafted polymer.

Figure 8 illustrates the two response mechanisms based on the two-layer picture described above. At low graft yields, the porous membrane layer dominates, and the expanded conformation of the grafted polymer in the pores above its pK_a gives rise to a reduced effective pore size in comparison with the collapsed state below the pK_a. This response mechanism was termed the "through-pore mechanism."[11] On the other hand, the membrane shows a higher permeability above the pK_a than below as the graft yield increases above a transitional graft yield. The response behavior is similar to PMAA hydrogel membranes.[12] The second type of permeability response is attributed to the hydrogel layer formed on the membrane surface: with increasing graft yield, more PMAA was located on the external membrane surface, and the hydrogel layer became thicker and dominant in controlling permeability changes, giving rise to the hydrogel type of permeability response. In addition, because more PMAA grafts are on the external surface of the water-grafted membrane [Fig. 8(a)] than the methanol–water–grafted membrane [Fig. 8(b)], the water–grafted membrane switches to the second type of response at a lower graft yield.

In summary, the permeability and response behavior of a responsive polymer-grafted porous membrane would be tailored by controlling the graft location, which may be achieved by varying grafting solvent.

Effect of Permeant Size

To investigate the effect of solute size on the permeability response of the membrane grafted in water with 387% graft yield, vitamin B_{12} and fluorescein isothiocyanate (FITC) dextrans with different molecular weights were selected as the permeants. The permeability response was measured as the ratio of permeabilities in pH 4.4 and pH 7.4. Figure 9 shows a maximum permeability ratio at an intermediate solute molecular weight. The phenomenon and explanation are completely consistent with those demonstrated in the study of the PE-*g*-PNIPAAm membrane.[7] Briefly, the effective pore size of the membrane changes due to the swelling or collapse of the graft polymer. Size exclusion occurs when the solute size is within an order or magnitude of the effective pore dimension of the membrane. The smallest per-

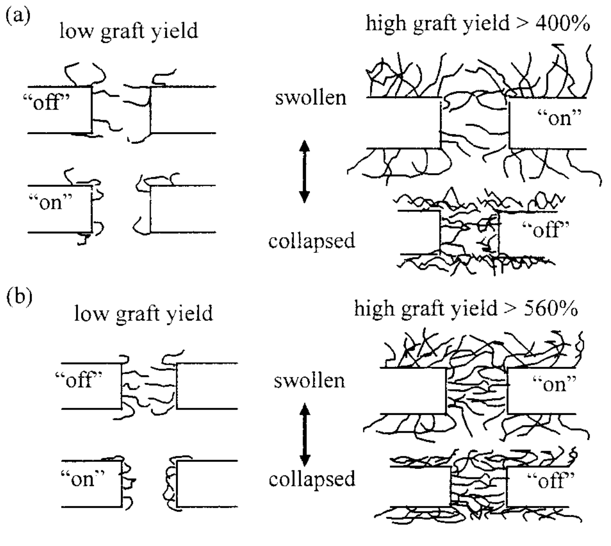

Figure 8 Schematic illustration of two types of permeability response of PMAA-grafted porous membranes prepared in (a) water and (b) methanol–water (1 : 3 by volume).

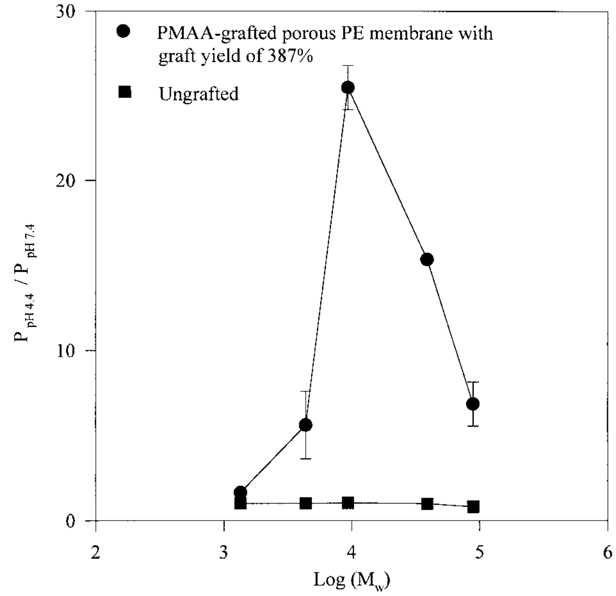

Figure 9 Effect of permeant molecular weight (M_w) on the permeability response of the membrane grafted in water. Error bars are standard deviation (n = 3).

meant is not significantly affected by the changing pore size since the effective pore size, even with swollen grafts, is much larger than the permeant. The largest permeant is not significantly affected by the changing pore size either because the effective pore size, in both the swollen and collapsed states, is comparable to the permeant size, and significant size exclusion exists in both states. For the intermediate-sized permeant, the change in pore size due to graft collapse or swelling represents a significant change in the extent of size exclusion, giving rise to the largest permeability response.

Dynamic Permeability Response

The reversibility of the membrane response was examined by dynamic permeability study using FITC-dextran with a molecular weight of 9400 as the permeant. The permeability in each cycle was calculated and presented in Figure 10, which shows the membrane permeability changes reversibly in response to a solution pH alternation between pH 2 and pH 7.4, which is consistent with the fast, reversible response observed previously on PE-*g*-PNIPAAm membranes[7] and as poly(acrylic acid)-grafted porous poly(propylene) membranes.[6]

CONCLUSIONS

1. Poly(methacrylic acid)-grafted porous polyethylene membranes with a wide range of graft yields can be prepared by photochemical graft polymerization.
2. Methanol can enhance the grafting at an appropriate volume ratio between methanol and water and increase the grafting inside the membrane pores, resulting in significant decrease in membrane swelling and thickness change in comparison with the use of a water solvent.
3. The membrane with low graft yields shows decreased permeability with the graft yield followed by increased permeability with further increasing graft yield.
4. Depending on the graft yield and graft location, two types of permeability response can be obtained. The membrane with low graft yields shows responsive behavior as a polymer-grafted porous membrane, while, the membrane with high graft yields shows permeability response as a hydrogel-like membrane. The membrane with more grafts on the external surface shows the hydrogel type of permeability response at a relatively lower graft yield.
5. The graft polymers inside the membrane

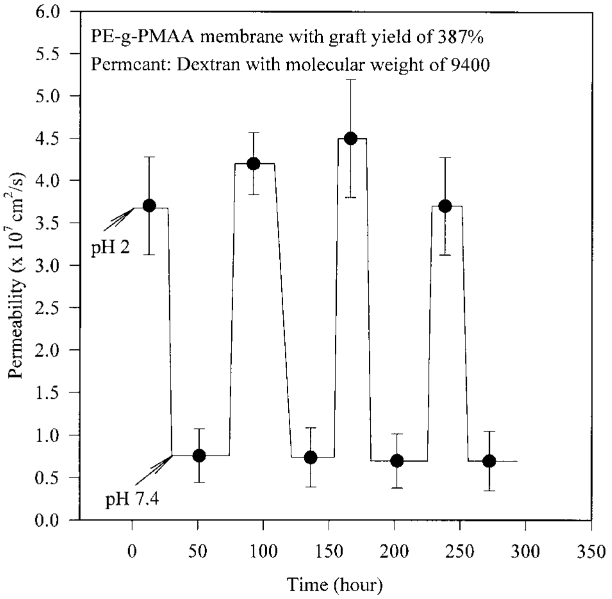

Figure 10 Dynamic permeability response of the membrane grafted in water to pH changes between 2 and 7.4. Error bars are standard deviation (n = 3).

pores promote the permeability response as the responsive polymer-grafted porous membrane.

6. The permeability response exhibits a maximum at an intermediate solute molecular weight.
7. The membrane response is reversible.

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