Synthesis and characterization of polymer networks made from poly(ethylene oxide) and polysiloxane

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In this paper, we describe the synthesis of copolymeric networks made from poly(ethylene oxide) (PEO) and a derivative of low-molecular-weight polydimethylsiloxane containing multiple glycidoxy functions (PGPMDMS). Upon addition of boron trifluoride etherate to homogeneous dichloromethane solutions of PEO and PGPMDMS, networks form via cationic ring opening of the glycidoxy groups, which add the terminal PEO hydroxyl and also homopolymerize. The molecular weight of PEO in the networks was varied from 690 to 17 700 and the PEO content was varied from 0 to 84 wt%. The reaction is sensitive to traces of water and the final network structure is affected by catalyst concentrations above 0.030 M. The networks containing PEO swell in water, and equilibrium swelling increases as the content of PEO increases. Equilibrium swelling does not increase with increases in PEO molecular weight because of intermolecular homopolymerization of PGPMDMS. Intentional oxidative degradation of the PEO component in these networks demonstrates that, for certain PEO-PGPMDMS compositions, a continuous PGPMDMS phase is formed. Because of the wide range of compositions that can be obtained, these networks are being used as a model system for studies on drug-releasing properties of hydrogels and on the blood compatibility of PEO-based materials.

(Keywords: poly(ethylene oxide); polysiloxane; cationic polymerization; hydrogels; biomaterials; interpenetrating networks)

INTRODUCTION

In recent years, polymeric materials containing poly(ethylene oxide) (PEO) have gained increasing attention from investigators in the field of biomaterials research. For blood-compatible materials, PEO appears to be a promising compound because evidence from a number of laboratories including ours has shown that increasing the PEO content in a material reduces protein adsorption to the material surface and lowers platelet retention[1–4]. While pure PEO hydrogels can be made by electron irradiation of water solutions of PEO[5], these materials contain >95% water at equilibrium and thus lack the requisite strength for blood-contacting devices such as catheters and vascular grafts. A polysiloxane component incorporated into the PEO networks, we believed, could act as a reinforcing agent and reduce water swelling and thereby improve material strength.

Polymers for the controlled release of drugs is another area of considerable interest among biomaterial scientists[6,7]. Permeability of drugs through polymers is a key property for these materials. Early efforts in this area focused on silicone rubber, i.e. crosslinked networks of poly(dimethylsiloxane) (PDMS). Hydrophobic drugs such as steroids readily permeate PDMS networks[8,9], but hydrophilic compounds exhibit low permeabilities[10,11]. Permeability measurements of PEO hydrogels, on the other hand, have demonstrated that they are permeable to vitamin B_{12}, a water-soluble compound[5]. This suggested to us that permeability of water-soluble drugs could be increased by incorporation of a hydrophilic component like PEO into polysiloxane. A two-component material comprising hydrophilic PEO and hydrophobic polysiloxane has the potential of being a versatile material whose composition may be adjusted depending upon the water solubility of the drug to be released. Our interest both in membranes for drug release and in durable materials for blood contact led us to develop copolymeric materials made from PEO and polysiloxane. In this paper, we report on the synthesis and physicochemical structure of crosslinked networks of PEO and a glycidoxy derivative of PDMS, poly(glycidoxypropylmethyl dimethylsiloxane) (PGPMDMS).

Synthetic routes for block and graft copolymers of PEO and PDMS have been reported elsewhere[12–14]. Examples are, for block copolymers, addition of allyl-terminated PEO to silane-terminated PDMS[12] or addition of amino-terminated PEO to isocyanate-terminated PDMS[13], and for graft copolymers, addition of allyl-terminated monoglycol PEO to poly(hydromethylsiloxane)[14]. A multifunctional polysiloxane suitable as a junction material for producing crosslinked networks with glycol-terminated polyethers was reported by Pekala and Merrill[15]. Allyl glycidyl ether was added via a platinum-catalysed reaction to poly(hydromethylsiloxane) (PHMS) having about 50 repeat units (*Figure 1a*). The functionalized compound, poly(glycidoxypropylmethylsiloxane) (PGPMS), was utilized to produce crosslinked materials of poly(propylene glycol) (PPG). Drawing on this work, we employed a similar junction material to produce crosslinked materials of polysiloxane and PEO. In order to reduce the occurrence of intramolecular reaction of glycidoxy groups (*Figure 1b*), we used a 50% random

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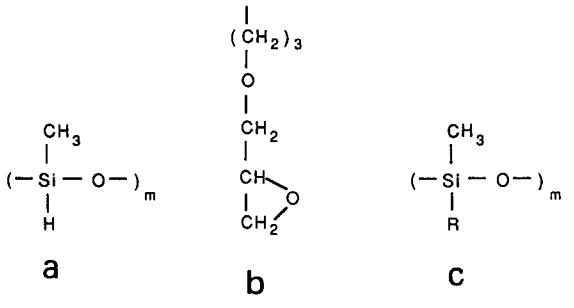

Figure 1 (a) Polyhydromethylsiloxane (PHMS). (b) Glycidoxypropyl group. (c) General representation of a polysiloxane compound: if R = methyl, (c) is PDMS; if R = glycidoxypropyl, (c) is PGPMS

copolymer of PGPMS and PDMS (*Figure 1c*, 50% R = methyl, 50% R = glycidoxypropyl) as the junction material, referred to hereafter as PGPMDMS, and in addition, reduced the functionality from around 50 to 5.

EXPERIMENTAL

Characterization of polymer precursors

Poly(ethylene oxide) (PEO), obtained from Polysciences (PEO 1000 and 3400), Fluka (PEO 2000, 6000 and 20 000) and Fischer Scientific (Carbowax 8000), was used without further purification except for rigorous drying to remove adsorbed water. The molecular-weight distribution of the PEOs was measured by gel permeation chromatography (g.p.c.) with a Waters 150-C g.p.c. system utilizing TSK PW3000 and PW4000 columns (Toya Soda). Data were collected by an IBM PC/XT via an A/D converter/interface (Data Translation DT2805) and analysed with software by Dennison[5]. Narrow molecular-weight standards of PEO from 210 to 39 000 daltons were obtained from Polysciences, Toya Soda and Pressure Chemical Co. Water (Millipore Hemo-RO and MilliQ filtration system) containing 0.02% sodium azide served as the mobile phase.

Poly(glycidoxypropylmethyl dimethylsiloxane) (PGPMDMS), 50% random copolymer, was obtained from Petrarch Systems Inc. or synthesized in-house from poly(hydromethyl dimethylsiloxane) (PHMDMS), 50% copolymer (Petrarch Systems) (see *Figure 1c*, 50% R = H, 50% R = CH_3) according to the method of Pekala and Merrill[15]. G.p.c. analyses of the polysiloxane compounds were carried out using a Solvent Delivery System model 6000A, Ultrastyragel 500 Å and 10^4 Å columns and differential refractometer R401 (Waters Associates) with h.p.l.c. grade dichloromethane as the mobile phase. Non-blended viscosity standards of PDMS (Petrarch Systems) were used to develop an approximate molecular-weight calibration curve. The number-average molecular weights of the polysiloxane compounds were determined by vapour-phase osmometry. Measurements were made of solutions in dimethylformamide at 90°C using a Knauer Vapor Phase Osmometer and benzil as the calibration standard. Infra-red (i.r.) spectroscopy was performed on a Perkin–Elmer 1430 Ratio Recording Infrared Spectrometer. Samples were analysed by attentuated total reflectance i.r. using a 45° ZnSe crystal (International Crystal Labs). PGPMDMS dissolved in $CDCl_3$ was analysed by proton n.m.r. on a Bruker WM 250. Quantitation of epoxy functions was carried out by direct titration using cetyltrimethylammonium bromide (Fluka) according to the method of Dijkstra and Dahmen[16].

Network synthesis

Synthesis of crosslinked polymer networks was carried out in a dry (relative humidity <11%) nitrogen atmosphere. All glassware was dried at 160°C for at least 4 h and cooled to room temperature in a nitrogen atmosphere. Plasticware was dried under active vacuum (10^{-3} Torr) at 40°C for at least 12 h prior to use. PEO or PGPMDMS was dissolved in dichloromethane at 15–20% concentration and the solution was dried over 3 Å molecular sieve (Union Carbide). The solution was filtered under nitrogen through a Millex-SR 0.5 μm filter. Removal of water was confirmed by Karl–Fischer titration (Mettler DL16). The concentration of polymer in solution was measured by g.p.c. In a dry box, the two polymer solutions were mixed together and anhydrous boron trifluoride etherate (Aldrich), diluted in dry dichloromethane 100–150 fold, was stirred into the solution. The reaction solution was transferred to polypropylene tubes or polyethylene moulds, which were then placed in a closed, saturated dichloromethane atmosphere and allowed to stand at room temperature. When it was established that the reaction leading to gelation was complete (usually by 12 h), dichloromethane was removed from the networks by evaporation at room temperature and pressure, or by graduated solvent exchanges from dichloromethane to ethanol to aqueous buffer solutions.

The composition of networks was varied in molecular weight of PEO from a nominal molecular weight of 1000 (M_n = 690) to 20 000 (M_n = 17 700) and in content of PEO from 0 to 84 wt%. The network composition is designated by these two parameters, e.g. 8K65 represents a network made with PEO 8000 containing 65% PEO and 35% PGPMDMS.

Characterization of networks and network reaction

Measurements of reaction rate were made by sequential sampling and analysis of an aliquot of reaction solution for epoxy concentration. Equilibrium swelling weights were obtained on polymer networks fully hydrated in 0.08 M sodium phosphate buffer containing 0.03% sodium azide (PBA) at room temperature. A sample was lightly tapped with filter paper before weighing and then dehydrated in a vacuum chamber containing Drierite (Hammond Drierite Co.). The weight of salts from the buffer was subtracted from the weight of the dried sample to obtain the final dry weight of the polymer. The equilibrium swelling weight ratio is the ratio of the weight of the swollen network to the final dry weight of the polymer. The weight fraction of aqueous solvent in the fully swollen polymer network is also employed to describe equilibrium swelling of a network. Three samples were tested for each composition.

Polymer samples that had not been subjected to solvent exchanges were used for analyses of the fraction of PEO and PGPMDMS not incorporated into the network during synthesis. To determine the amount of PEO not incorporated into the network, a 0.2–0.8 g sample was placed in 10 ml water and agitated on a shaking platform (Warner–Chilcott Laboratories). After one week, the concentration of PEO in the aqueous solution was measured by g.p.c. To determine the amount of PGPMDMS not incorporated into the network, a sample of polymer was swollen in 10 ml benzene for one week. The benzene was evaporated and the residue was redissolved in 2 ml toluene. The concentration of

PGPMDMS in toluene was measured by i.r. spectroscopy as follows: the baseline of the i.r. crystal was subtracted from the absorbance spectrum and the ratio of the absorbance at 804 cm^{-1}, corresponding to the siloxane methyl vibration, to the absorbance at 2099 cm^{-1}, corresponding to the aromatic ring stretch in toluene, was calculated. This ratio is linear with PGPMDMS concentration up to 2% concentration and is independent of PEO concentration. Three samples were tested for each composition.

Oxidative degradation of PEO chains in the networks was accomplished by placing water-swollen networks in a 5% hydrogen peroxide solution at 70°C for 1 week or in a 0.5% sodium hypochlorite solution at room temperature for 2 days.

Experiments were carried out to measure rates of epoxy consumption during network formation. The effect of water, PEO concentration and catalyst concentration on reaction rates was studied. The relationship of catalyst concentration to the swelling ratio and fraction of extractable material from the networks and the effect of catalyst on the molecular weight of PEO were characterized. Swelling properties of the networks and the fraction of PEO and PGPMDMS not incorporated into the networks as a function of the PEO content and molecular weight also were examined. The structure of the networks was probed by the oxidative degradation of the PEO component in the networks.

RESULTS

Characterization of polymer precursors

Table 1 lists the results of the molecular weights of PEOs determined by g.p.c. *Figure 2* shows chromatograms for several of the PEOs and demonstrates that the molecular-weight distributions are narrow ($M_w/M_n \leqslant 1.3$) and unimodal. Gel permeation chromatograms of PGPMDMS are shown in *Figure 3*. PGPMDMS obtained commercially, designated by the subscript 'P', was characterized by a broad ($M_w/M_n = 2.0$), bimodal distribution, whereas the compound synthesized in-house, designated by the subscript 'C', had a narrow ($M_w/M_n = 1.2$), unimodal distribution. The weight- and number-average molecular weights determined by g.p.c. are approximations, representing the molecular weights of PDMS with radii equivalent to PGPMDMS in dichloromethane. Direct measurement of M_n was made with vapour-phase osmometry, which gave values of 1760 and 920 for $PGPMDMS_P$ and $PGPMDMS_C$, respectively.

Epoxy titrations of the polysiloxane compounds yielded values of 301 and 282 g per mole of epoxy functions for $PGPMDMS_P$ and $PGPMDMS_C$, respectively.

The i.r. spectrum of $PGPMDMS_P$ is shown in *Figure 4*. As PGPMDMS is synthesized by addition of allyl glycidyl ether to PHMDMS[15], the absence of an absorption band at 2140 cm^{-1} (Si–H stretch) is evidence that addition was carried to completion. Moreover, the absence of a peak at 1660 cm^{-1} (C=C stretch) demonstrates that no residual allyl glycidyl ether is present in the polysiloxane preparation. Of particular note is the peak at 910 cm^{-1}, which corresponds to the epoxy group, the function that reacts in network formation. The i.r. spectrum of $PGPMDMS_C$ showed these same features. The proton n.m.r. spectrum of

Table 1 Molecular weight of PEO measured by gel permeation chromatography

Nominal molecular weight	M_w	M_n	M_w/M_n
1000	880	690	1.28
2000	1910	1690	1.13
3400	3050	2580	1.18
6000	6200	5680	1.09
8000	9700	8620	1.12
20000	22900	17700	1.30

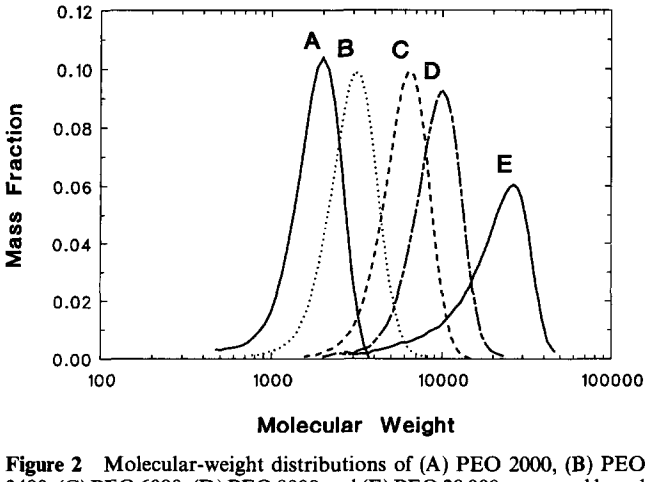

Figure 2 Molecular-weight distributions of (A) PEO 2000, (B) PEO 3400, (C) PEO 6000, (D) PEO 8000 and (E) PEO 20 000 measured by gel permeation chromatography

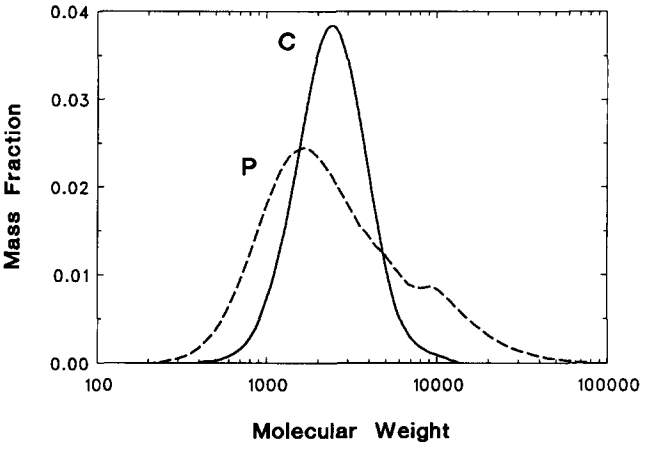

Figure 3 Molecular-weight distributions of PGPMDMS: (P) obtained from Petrarch Chemicals and (C) synthesized in-house by E. Chaikof

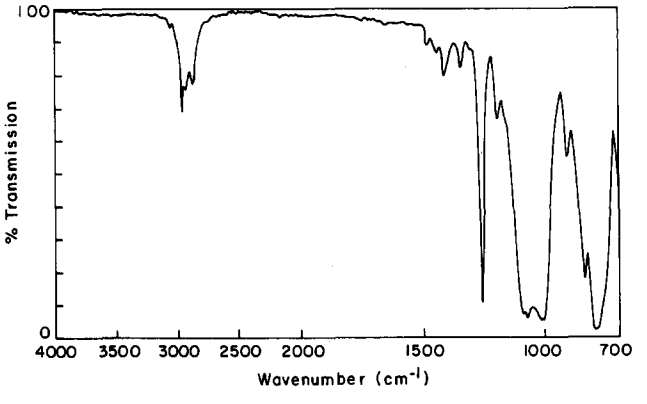

Figure 4 Attenuated total reflectance i.r. spectrum of $PGPMDMS_P$

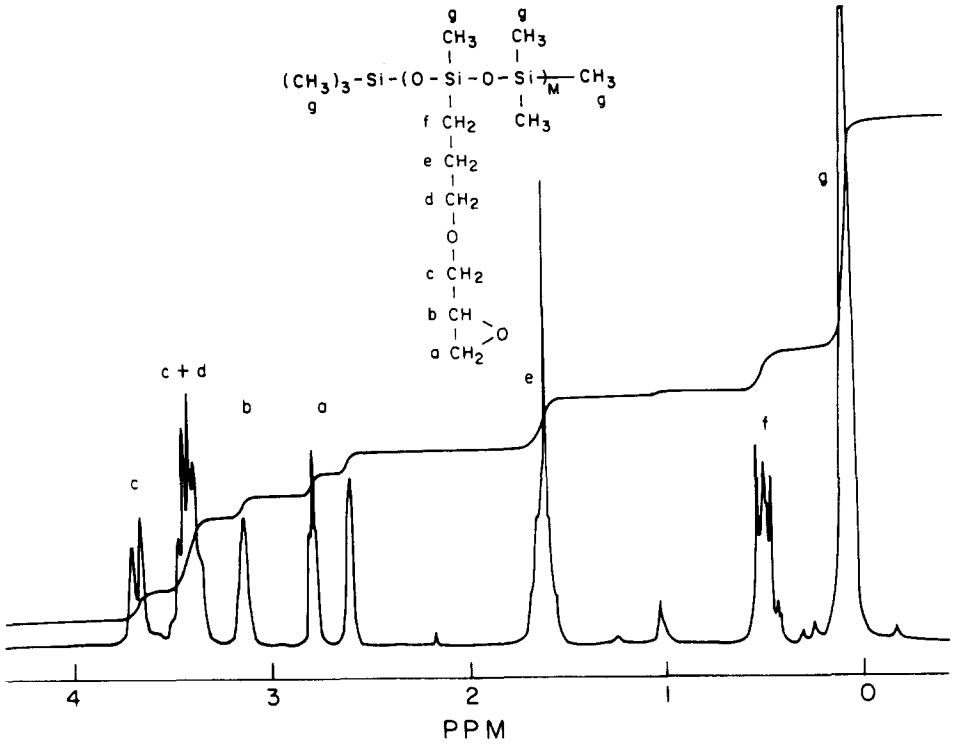

Figure 5 250 MHz ^{1}H n.m.r. spectrum of PGPMDMS$_P$ in $CDCl_3$

PGPMDMS (*Figure 5*) contains information on the average number of epoxies per polysiloxane molecule. Peak g represents protons of methyl groups bonded to silicon either at a chain end or in the backbone, and peak b corresponds to the proton of the β-epoxy carbon. For PGPMDMS$_P$, the g/b ratio was 11.0; therefore, it contains 6.0 epoxy groups per molecule on average. For PGPMDMS$_C$, g/b was 11.5 and thus contains 4.8 epoxy groups per molecule.

Characterization of networks and network reaction

In formation of networks of PEO and PGPMDMS, boron trifluoride etherate catalyses the cationic ring opening of the glycidoxy group of PGPMDMS by terminal PEO hydroxyls[17] (*Figure 6*). If this were the only possible reaction, then in the terminology of end-linked model networks, PEO would be considered the bifunctional 'chain' component and PGPMDMS would take the role of pentafunctional 'junction' material. However, other reactions also occur as demonstrated by the data shown in *Figure 7* where the rate of consumption of epoxies is illustrated for two polymer networks: 2K50 and PGPMDMS. In both cases, nearly complete conversion of epoxies was measured even though in PGPMDMS there are no hydroxyls present initially, and in 2K50 there is nearly a 3:1 molar ratio of epoxies to hydroxyls present initially. Other possible reactions involving epoxies are (a) epoxy ring opening by water to form a diol, (b) epoxy ring opening by propylene glycol created by the reaction of PEO and PGPMDMS, (c) intramolecular epoxy–epoxy coupling, and (d) intermolecular epoxy–epoxy coupling or homopolymerization. Reactions (b) and (d) can produce a more highly crosslinked network whereas (a) and (c) do not. The fact that a crosslinked network was obtained in the BF_3-catalysed reaction of PGPMDMS alone proves that reaction (d) definitely occurs in the absence of PEO. Thus

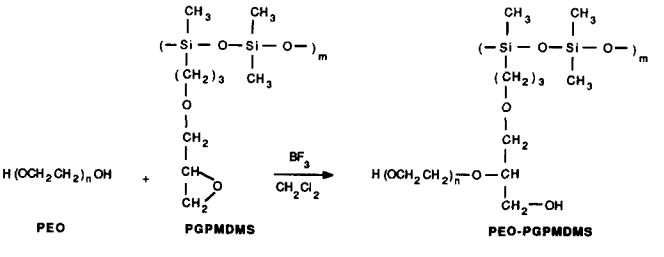

Figure 6 Chemical reaction of PEO and PGPMDMS during network formation

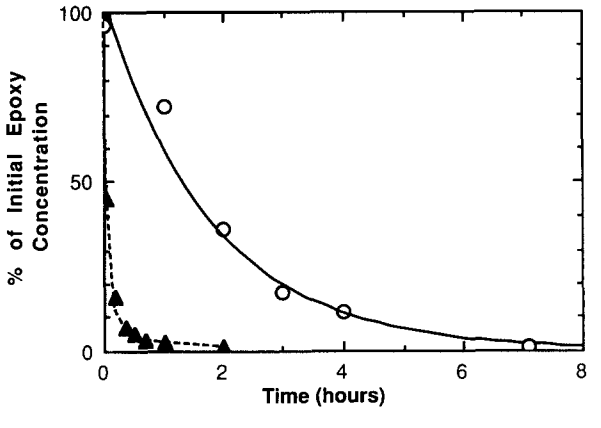

Figure 7 A comparison of rates of epoxy consumption during network formation with and without PEO. The BF_3 concentration was 15 mM in both cases: (○) 9.6% PEO 2000 and 9.6% PGPMDMS$_P$ in dichloromethane (2K50); (▲) 9.6% PGPMDMS$_P$ in dichloromethane. In both cases, nearly complete conversion of epoxies is measured

pure PGPMDMS networks may be synthesized by the same method as the synthesis of PEO–PGPMDMS networks. Analysis of the rate data shown in *Figure 7* indicates that the reaction rate for 2K50 may be modelled as a first-order reaction in epoxy concentration: a least-squares linear regression of time vs. $\ln(C/C_0)$ yields

$r^2 = 0.986$. The reaction of pure PGPMDMS, however, is better modelled as a second-order reaction in epoxy concentration ($r^2 = 0.986$; a first-order model gives only $r^2 = 0.910$). A second-order reaction would be expected in a bimolecular epoxy–epoxy coupling reaction.

In the experiment illustrated by *Figure 7*, the concentrations of PGPMDMS and BF_3 were held constant for the two network syntheses. Addition of PEO reduced the rate of epoxy consumption even though the presence of PEO increases the types of reactions in which epoxies are consumed. This seeming paradox perhaps is understood in terms of the role of BF_3 in the reaction when PEO is present. BF_3 complexes with the epoxy oxygen and increases the susceptibility of the β-carbon in the glycidoxy group to nucleophilic attack, such as by hydroxyls of PEO chain ends[18]. However, BF_3 also readily complexes with oxygens of other sources such as ether and hydroxyl oxygens of PEO and with water as well[17,18]. This quenching of the BF_3 activity is further evidenced by a study of the relationship between BF_3 concentration and initial reaction rates. For a fixed network composition, the initial rate of reaction increases as BF_3 concentration increases, but the rate of rise is greater than a linear function (*Figure 8*). The disproportionately low reaction rate at low BF_3 concentration suggests that the reaction solution contains a compound or compounds that inactivate a certain amount of catalyst. This amount of inactivated catalyst represents a progressively smaller fraction of the total amount of catalyst as the catalyst concentration is increased. The BF_3 quenching activity of water is demonstrated by the experiment illustrated in *Figure 9*: when the concentration of water was increased 12 fold from 26 mM to 311 mM, the reaction rate decreased by a factor of 13, and a network failed to form. Water promotes the formation of boron trifluoride hydrates[18], which have no catalytic activity. Consequently, protocols were developed to eliminate water from the reaction solutions by drying the reagents and conducting the polymerization in a dry atmosphere. Karl–Fischer analysis of PEO and PGPMDMS solutions after drying with molecular sieve showed that the polymer solutions

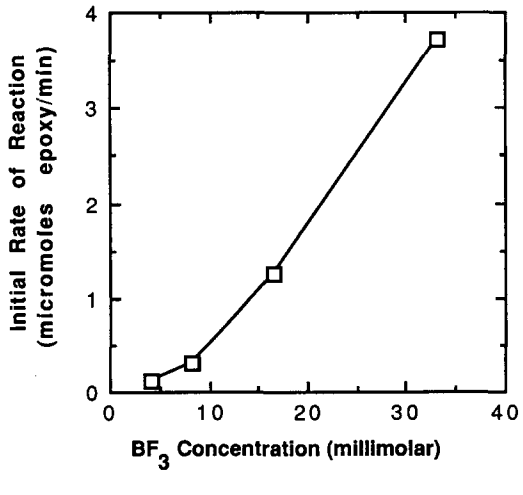

Figure 8 The relationship between BF_3 concentration and initial reaction rates of PEO–PGPMDMS network formation (1K46), measured by disappearance of epoxies. The rate of increase is greater than a linear function, which suggests that the reaction solution contains a compound or compounds that quench a fractional amount of BF_3 activity

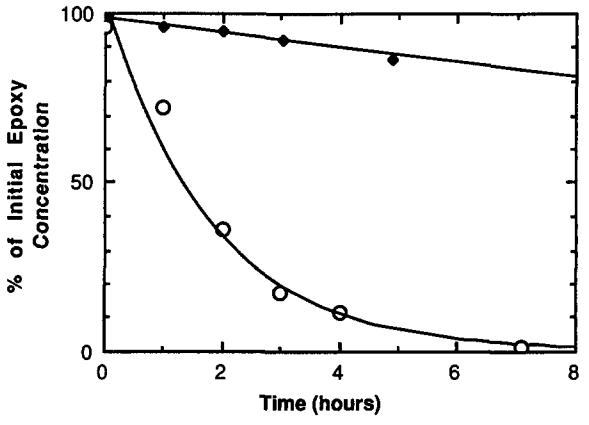

Figure 9 The effect of water on the kinetics of network reaction of PEO–PGPMDMS (2K50). The BF_3 concentration was 15 mM in both cases. Water concentration: (○) 26 mM; (•) 311 mM

contained less than 0.0004 g water per gram PEO and 0.0002 g water per gram PGPMDMS.

The possibility of BF_3 complexation with ether oxygens in PEO suggested to us that BF_3 might cause PEO chain scission. This effect was tested for by adding BF_3 to a solution of PEO at the catalyst concentration used in network synthesis (11 mM). After 24 h of reaction, the molecular-weight distribution of PEO was measured and compared with a control with inactive catalyst. PEO degradation occurred to a small extent, causing a 4% decrease in M_n.

An unusual observation was made when BF_3 concentrations greater than 100 mM were used in network synthesis: the solution gelled into a network but gradually redissolved. This effect was observed even during synthesis of pure PGPMDMS networks and, therefore, is not attributable only to PEO chain scission. To examine the effect of BF_3 on network structure in more detail, the equilibrium swelling ratio and sol fraction (the fraction of extractables in the network) were studied as a function of BF_3 concentration. Equilibrium swelling increases when network degradation occurs because there are fewer crosslinks providing retractive elastic forces to offset osmotic swelling forces[19]. The results, shown in *Figure 10*, demonstrate that above 45 mM BF_3, a large increase in equilibrium swelling and sol fraction occurs, but below 30 mM BF_3, the effect of catalyst concentration on these variables is small. To minimize the effect of BF_3 concentration on polymer properties, all subsequent syntheses were carried out at BF_3 concentrations less than 12 mM. Although the reason for the liquefaction of the network when exposed to high concentrations of BF_3 is unknown, it seems reasonable to suppose that a degradation of ether bonds is occurring, which disconnects the original network partially or completely.

In the crosslinked networks, a measurable quantity of PGPMDMS and PEO was extracted by water and benzene (*Figure 11*). Incomplete incorporation of PGPMDMS into a network is believed to occur, in part, because PGPMDMS, by virtue of the way its precursor PHMDMS is prepared (ring-opening reaction of 'D4' monomer, octamethyltetrasiloxane, with hydromethylsiloxane), contains a small fraction of PDMS. PDMS has no reactive glycidoxy groups and therefore cannot be connected into the network. Another factor that may account for incomplete incorporation of PGPMDMS is intramolecular reaction of glycidoxy groups. The

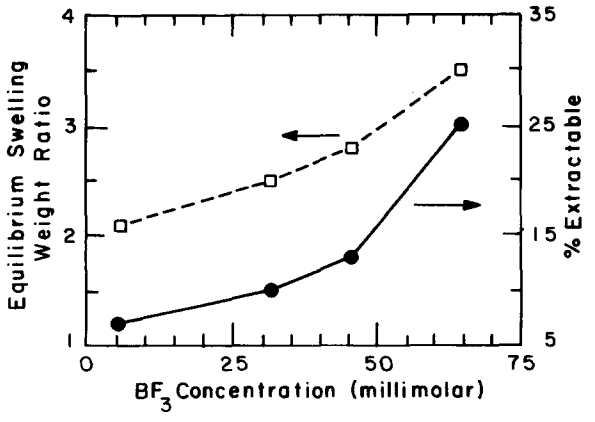

Figure 10 Effect of catalyst concentration on (□) equilibrium swelling weight ratio and (●) per cent extractables of PEO–PGPMDMS 2K50

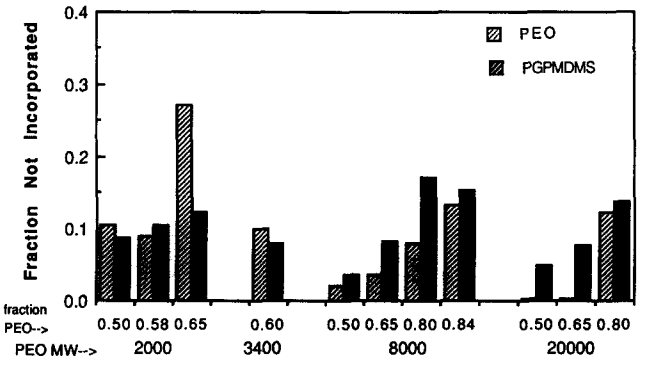

Figure 11 In synthesis of PEO–PGPMDMS networks, not all the PEO and PGPMDMS is incorporated into the network. The amount of unincorporated PEO or PGPMDMS as a fraction of the initial amount of PEO or PGPMDMS was determined by extracting the networks with water and benzene, respectively

incomplete incorporation of PEO may be related to chain scission and to competition from the PGPMDMS epoxy–epoxy coupling reactions. *Figure 11* shows that, as the molecular weight of PEO is increased, the fraction of PEO not incorporated decreases. This is probably related to the increase in the molar excess of epoxies relative to hydroxyls as PEO molecular weight is increased. Another trend evident from the data in *Figure 11* is that, as the PEO fraction in the networks increases, the percentage of PEO and PGPMDMS not incorporated in the networks increases. As PEO concentration is increased, the concentration of ether and hydroxyl oxygens increases, and the role these sources of oxygen play in quenching BF_3 activity may explain this observation.

In the completely dry state at room temperature, PEO–PGPMDMS networks containing >50% PEO are milky white, but when heated above 66°C, the T_m of PEO, the PEO crystallites melt and the materials become clear. The networks also become transparent when placed in water as a result of the highly effective property of water to hydrogen-bond to PEO and disrupt its crystalline structure[20]. The networks swell in water and *Figure 12* summarizes the equilibrium swelling data in aqueous buffer (0.08 M sodium phosphate, pH 7.4). As expected, an increase in the content of the hydrophilic polymer, PEO, increases swelling. On the other hand, no significant change in swelling is observed as PEO molecular weight is increased for a fixed mass fraction of PEO. This behaviour is contrary to that predicted from Flory's model of ideal networks[19]. The divergence from Flory's predictions is not surprising because an important criterion for an ideal network is not met by the PEO–PGPMDMS networks: Flory's model stipulates that the junctions be volumeless, discrete points in the network, whereas in PEO–PGPMDMS networks, the junctions (PGPMDMS) constitute a significant fraction of network volume, and in many compositions, as will be shown below, form a continuous phase in the network.

PGPMDMS, in the absence of PEO, forms a continuous network upon addition of BF_3. To assess whether PGPMDMS forms a continuous phase in networks containing PEO, PEO–PGPMDMS networks were intentionally exposed to strongly oxidizing conditions to degrade the PEO component. Under the conditions used, pure PEO hydrogels formed by irradiation crosslinking completely dissolved whereas pure PGPMDMS crosslinked networks remained intact. The results for PEO–PGPMDMS networks of varying composition and molecular weight of PEO are shown in *Figure 13*. Open circles represent PEO–PGPMDMS networks that disintegrated after PEO oxidation and filled circles represent networks that were continuous structures after PEO degradation. At a low initial fraction of PEO, the PGPMDMS component in the networks is continuous but, as the PEO fraction is increased, a transition to a discontinuous PGPMDMS structure occurs above which the networks disintegrate upon PEO degradation. For example, networks formed from PEO 8000 undergo the transition between 50 and 65% PEO.

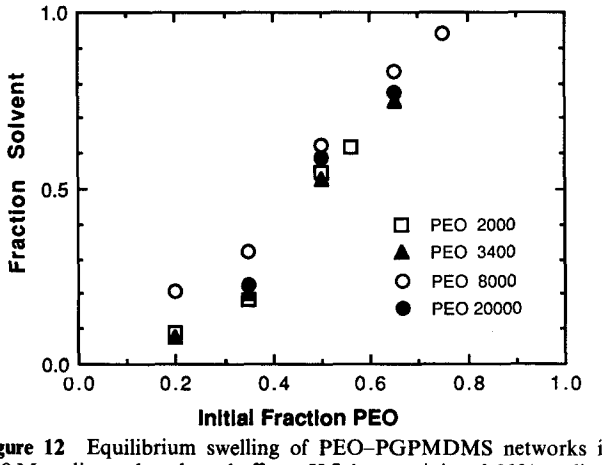

Figure 12 Equilibrium swelling of PEO–PGPMDMS networks in 0.08 M sodium phosphate buffer, pH 7.4, containing 0.03% sodium azide

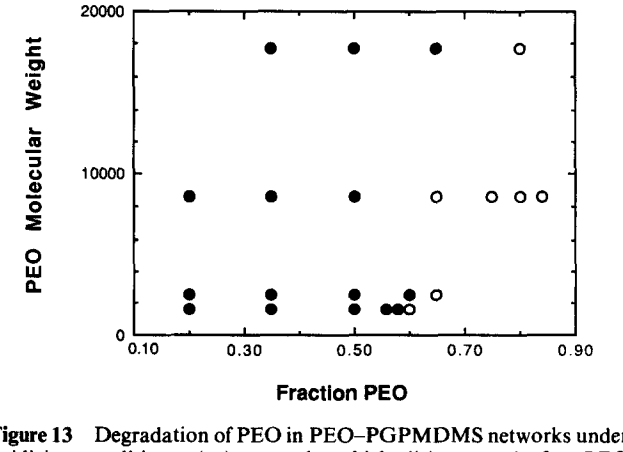

Figure 13 Degradation of PEO in PEO–PGPMDMS networks under oxidizing conditions: (○) networks which disintegrated after PEO degradation; (●) networks which remained intact

The point of transition occurs at an increasingly higher fraction of PEO as the molecular weight of PEO increases. As the initial fraction of PEO decreases or as the molecular weight of PEO increases, the number of hydroxyl ends per unit mass decreases, the proportion of epoxies available for PGPMDMS homopolymerization increases, and the probability for formation of a continuous PGPMDMS phase increases. The observation that many compositions of PEO–PGPMDMS networks do not disintegrate after PEO degradation demonstrates that, during network formation, in addition to cross-reaction of PEO and PGPMDMS, homopolymerization of PGPMDMS also takes place.

DISCUSSION

The synthesis procedure presented here for preparation of crosslinked networks made from PEO and polysiloxane offers a method of preparing materials with a wide range in both the fraction and molecular weight of PEO. The networks form via BF_3-catalysed cationic polymerization of PEO and PGPMDMS, a modified PDMS compound containing approximately five glycidoxy groups.

The studies in this paper demonstrate the importance of controlling the concentration of water and catalyst during network synthesis. We showed that BF_3 activity is quenched by water and that it is therefore critical to dry reagents prior to use and to carry out the reaction in a dry atmosphere. Catalyst concentration affects network properties such as equilibrium swelling and sol fraction. BF_3 affects network properties because it promotes PEO chain scission and probably also the degradation of other ether bonds in the network. Concentrations of BF_3 below 0.030 M, however, resulted in a minimal effect on swelling and sol fraction and, at a BF_3 concentration of 0.011 M and all other conditions used in network synthesis, PEO molecular weight was decreased by less than 4%.

The experiments described here demonstrate that a complex set of reactions occur during network formation. In addition to the end-linking of PEO chains with PGPMDMS junctions, homopolymerization of PGPMDMS also takes place. *Figure 14* is a cartoon illustration of possible distributions of PEO and PGPMDMS in a network. Proceeding from A to D represents a progressive build-up of the PGPMDMS phase. This may be due to a lowering of the concentration of PEO or an increase of the molecular weight of PEO (i.e. a decrease in the concentration of reactive PEO chain

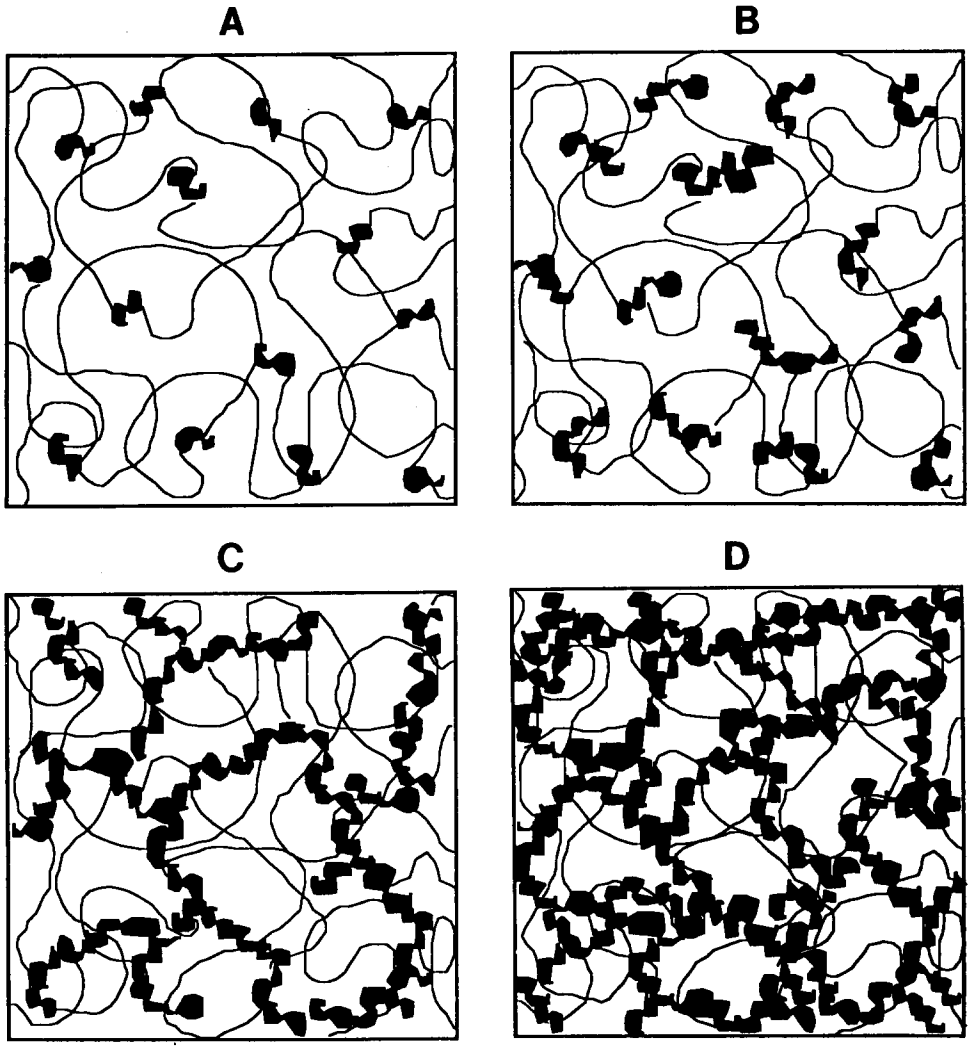

Figure 14 Schematic representation of PEO–PGPMDMS networks in a hydrated state. The PGPMDMS component is depicted as the black area; the PEO component is depicted as the thin lines; the white background is water. In (A) and (B), PGPMDMS is a discontinuous phase in the hydrogel phase; in (C) and (D), the PGPMDMS phase is continuous. Within structures such as (C), a high interfacial region exists between hydrophobic and hydrophilic phases

ends), or both. Structures such as C and D contain a continuous PGPMDMS phase and could be called interpenetrating networks with chemically linked constituents[21,22]. These interpenetrating networks do not disintegrate when the PEO component is degraded.

Further insight into the distribution of the PEO and PGPMDMS components in the network was provided by experiments on the drug release of a water-soluble compound, protriptyline, from a series of networks of varying composition[23]. The effective diffusivity of the drug in the polymeric network decreased by a factor of 40 when the composition of PEO (molecular weight 8000) was decreased from 50 to 35% network compared to only a 13-fold decrease over the range of 100 to 50% PEO. The greatly reduced permeability of the water-soluble drug in networks containing 35% or less PEO suggests that PEO is a discontinuous phase in those networks—the hydrophilic drug cannot diffuse solely in a continuous hydrogel phase but must diffuse, at least part of the time, in the hydrophobic PGPMDMS phase where transport is much slower. Studies on oxidative degradation of the PEO–PGPMDMS networks and the drug-releasing behaviour of the networks indicate that for certain compositions, for example 8K50, two continuous phases may exist—one from PEO end-linked by PGPMDMS and the other derived from PGPMDMS covalently connected.

An interesting feature of structure C in *Figure 14* is the existence of a large interfacial region between the hydrophilic phase of PEO and water and the hydrophobic phase of PGPMDMS. Based on studies of sorption of drugs into these networks, the interfacial region appears to be a favourable environment for amphiphilic drugs[23]. The interfacial region may act as a collection of microreservoirs for sustained desorption of drug.

The application of these materials as surfaces that delay or arrest the formation of blood clots is under active investigation in our laboratory. Preliminary studies in baboons showed that the deposition of platelets and fibrinogen on PEO–PGPMDMS materials containing 35% or more PEO is 2–16 times lower than on expanded polytetrafluoroethylene (e-PTFE), and that platelet and fibrinogen deposition decreases as the PEO content and molecular weight in PEO–PGPMDMS materials is increased[24]. Further studies are under way.

In conclusion, these crosslinked networks made from poly(ethylene oxide) and polysiloxane, because of the wide range of compositions that can be obtained, represent an interesting group of materials for studies on drug-releasing properties of hydrogels and on the blood compatibility of PEO-based materials.

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