

Some Practical Aspects of Preparing Polymeric Hydrogels via γ -Irradiation

INTRODUCTION

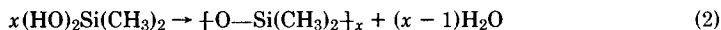
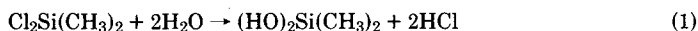
A considerable literature covers the preparation and properties of hydrogels for biomedical application (for a recent review see, e.g., Tighe¹). The failure to emphasize practical problems in these reports should not be taken to imply, however, that such difficulties are absent. The preparative techniques usually involve polymerization or copolymerization in the presence of a crosslinking agent. Bulk polymerization is often used, or, alternatively, reaction in an aqueous medium if the monomers are fairly soluble in water.²

The present authors are currently studying copolymers made from a very hydrophilic vinyl lactam, a hydrophobic alkyl acrylate, and a hexafunctional methacrylate. The desired properties of the hydrophilic product include (a) optical and textural homogeneity, (b) minimal content of residual monomers and (c) ease of machinability. Bulk copolymerization in vacuo at 21°C initiated by γ -irradiation from a ⁶⁰Co source is employed. Resolution of certain experimental problems, which arose in this work, should be of interest to others in the field, and this constitutes the theme of the present communication.

SPECIFIC ASPECTS

Siliconization of Ampoules and Adventitious Polymerization

Initially, copolymerization was effected in sealed, borosilicate glass ampoules (length 125 mm, diameter 16 mm, thickness 1 mm), which had been outgassed by freeze-thaw cycles. After γ -irradiation, removal of the clear polymer rod was extremely difficult due to its strong adhesion to the glass surface. At high contents of the hydrophilic monomer, this adhesion was exceptionally tenacious. In contrast, the crosslinked homopolymer of the acrylate was very easily removable from the ampoule. Consequently, the internal surface of the ampoule was rendered hydrophobic by prior siliconization using Repelcote (Hopkin and Williams Ltd., Romford, U.K.) according to the following recommended procedure. After standard cleaning operations and drying, 1–2 mL Repelcote were introduced and distributed evenly over the interior by shaking the ampoule. The excess of liquid was then poured off. A thin internal silicone coating was produced by heating the ampoule in an air oven for ca. 3 h at 60–80°C. Repelcote is a 2% w/v solution of dichlorodimethyl silane in 1,1,1-trichloroethylene, and the siliconization proceeds via reaction with trace amounts of water vapor³:



After outgassing, the monomer mixture in the siliconized, sealed, ampoule at -196°C was allowed to attain room temperature. On certain occasions during this thawing period the development of a white precipitate with evolution of heat was noted. This spread rapidly (ca. 5 min) to total formation of a white spongy solid,⁴ which was readily detachable from the ampoule, thus verifying the efficiency of the siliconization. However, the polymerization occurred at low temperature in the absence of chemical initiator or γ -irradiation.

The fact that this effect happened irregularly suggests the possible presence of a substance considered to have been completely removed. Moreover, the low temperature initiation is indicative of cationic polymerization.⁵ Both factors can be attributed plausibly to initiation by HCl [see eq. (1)]. Consequently, the procedure was amended by rinsing the ampoule twice with water after siliconization at 60–80°C and then drying it in a vacuum oven before introduction of the monomer solution. This amendment was successful in both facilitating removal of the final rod and in preventing prepolymerization.

Adventitious prepolymerization was observed also under different circumstances. When evac-

uating (10^{-5} mm Hg) the frozen monomer mixture during outgassing, a high frequency tester (Tesla) was applied to a glass-blowing joint in order to locate any possible leaks from pinholes. No effect was observed, but during the thawing period white spongy polymer developed rapidly. Here again ionic initiation is indicated, but in this case via ionization of gaseous molecules at very low pressure. Subsequently, the Tesla testing was conducted on ampoules only prior to introduction of the monomer mixture.

γ -Induced Copolymerization

By appropriate optimization of the composition of monomer mixture and the total radiation dose, it was possible to obtain polymer rods of the desired properties. Full details will be published later. Here it is pertinent to indicate only certain experimental conditions which were found to affect the polymer properties adversely.

(a) If the dose for the desired properties is obtained at dose rates (R) above a certain value (R_c), then the precise dose rate is not critical. However, at dose rates below this minimum value, the product can vary in form from a popcorn texture (at $R < R_c$) to a spongy consistency (at $R \ll R_c$). This loss of homogeneity may well be due to the effect of molecular weight on compatibility, since, low R increases the kinetic chain length.

(b) At $R > R_c$ it is possible to obtain the desired properties even if the total dose is interrupted by periods of nonirradiation. However, this was found to be true only if the interruptions occur within the post-gel region (i.e., after solidification). Within the pre-gel region, short interruptions give rise to a popcorn texture, while a spongy white product is formed if the interruptions are long. Here again incompatibility at high chain length can afford a qualitative explanation. Thus, when an interruption begins, the concentration of active radical species is much smaller than that obtaining under continuous irradiation. Therefore, the rate of initiation is reduced and the kinetic chain length correspondingly increased.

Other Methods of Copolymerization

(a) When the monomer mixture was irradiated under an atmosphere of gaseous N_2 instead of under vacuum, there was no apparent difference in the conversion or properties of the solid product. However, after cutting the rod into thin discs and swelling in water, some difference became manifest in the swollen state. Thus for the polymer prepared under vacuum the swollen hydrogen was clear and homogeneous, whereas when gaseous nitrogen had been used the clear swollen discs manifested some stream-type optical strain. The development of optical strain has been postulated⁶⁻⁸ to arise from nonuniform heat distribution during polymerization. It is possible that, under an atmosphere of nitrogen, the heat distribution within the polymerizing system is predominantly via the rather inefficient convection by nonpolymerizing molecules of dissolved nitrogen. In the absence of the latter, i.e., *in vacuo*, the heat is dissipated more uniformly.

(b) A white, spongy polymer similar to that mentioned in the previous items was also produced very rapidly by bulk polymerization *in vacuo* at 50°C when employing a chemical free radical initiator instead of γ -irradiation. Several concentrations ($2 \times 10^{-4}M$ – $2 \times 10^{-2}M$) of 4,4'-azobiscyanopentanoic acid were used, but the same form of polymer was obtained even at the highest initiation rate. We have been unable to offer any reasonable explanation for this finding, although auto-acceleration⁹ must be at least partly involved. There are precedents for chemically initiated bulk copolymerization to yield both heterogeneous¹⁰ and homogeneous¹¹ hydrogels. However, we have not pursued this route any further by varying the temperature and nature of initiator, in view of the successful implementation of the present medium of γ -irradiation.

Removal of Copolymer

After irradiation it is necessary to remove the solid rod of xerogel intact from the sealed ampoule. The common device of "hot-spotting" (i.e., applying a molten glass rod to a moistened scratch on the glass) did enable the rod to be detached, but a severe localized burn mark was left on the polymer. This was obviated by scratching the ampoule spirally with a glass cutter and then tapping it gently with a metal bar. By this means the rod could be detached perfectly from the broken ampoule.

Post-Polymerization Curing

Following the previous stage the rod was post-cured in an oven for 24 h at 105°C and then cooled to room temperature in a vacuum desiccator. Complete conversion was verified from comparison of the weights of initial monomer mixture, the rod after irradiation and the rod after oven curing (the presence of any involatile oligomers assessable by subsequent extraction experiments is not relevant in this context). The oven-cured rod remained colorless and was cut into thin discs (see following item) for further characterization. It was noted, however, that if discs are cut after irradiation and then subjected to oven curing, they develop an intense amber coloration. Thin discs of high surface area are clearly more susceptible to surface oxidation at high temperature, and it was concluded to be preferable to effect curing of polymer in the uncut rod form.

Cutting Uniform Discs from Polymer Rod

The copolymers range from elastomers to glasses at high and low contents, respectively, of the acrylate. Several types of characterization necessitate that the samples be in the form of uniform thin discs of thickness ca. 0.2–1.0 mm. During the lathe cutting of discs from the polymer rod, elastomeric samples collapsed because of the heat developed. With very glassy copolymers, the disc usually broke off from the rod to give a washer type of disc with a central hole.

Problems of this nature are not normally encountered with the specialized lathes used specifically in the contact lens industry, but these are expensive and not generally available in a polymer research laboratory. A simple device for slicing rather thicker specimens from a block of leathery hydrogel has been improvised elsewhere,¹² but this is unsuitable for more glassy materials.

For the present materials over almost the entire composition range (but not for the two crosslinked homopolymers) we have succeeded in overcoming the previously mentioned difficulties by means of the following simple procedure (see Fig. 1), which involves only a standard engineering workshop lathe (Model 5 × 20 Chipmaster, Colchester Lathe Manufacturers, Ltd., Colchester, U.K.) and double-sided adhesive tape (R. S. Components, Ltd., Stockport, U.K.).

(i) The polymer rod is clamped firmly in the lathe head [Fig. 1(a)] and, with the blade moving horizontally, the rod is trimmed to a uniform diameter. Then, with transverse movement of the blade, the exposed end is parted off to give a smooth finished surface A.

(ii) A disc of thickness greater than required is then cut off with a small hacksaw leaving a rough surface B [Fig. 1(b)].

(iii) A brass rod with a smoothed base C is next clamped in place of the rod with C outermost.

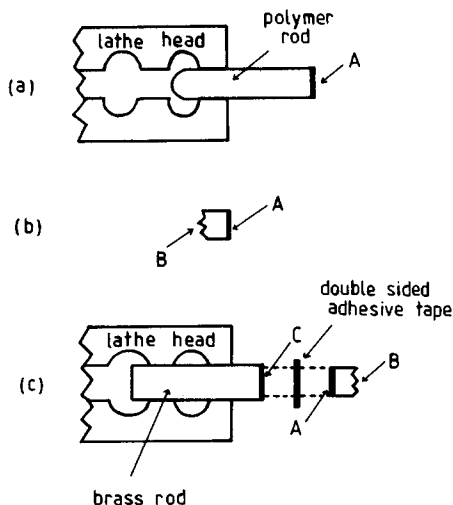


Fig. 1. Procedure for cutting uniform, thin disc from rod of copolymer (for explanation, see text).

Double-sided adhesive tape is affixed to C and then surface A of the disc is affixed to the other adhesive side of the tape [Fig. 1(c)].

(iv) Several transverse movements of the blade suffice to part off the exposed rough surface B to the required thickness. The finished disc and tape are then detached together by sliding the tape gently in a direction parallel to surfaces A, B, and C. Finally the tape is peeled off from surface A.

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