

Preparation of Latex Carriers for Controlled Release by Concentrated Emulsion Polymerization

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Synopsis

Spherical latexes of submicron diameter containing a model hydrophobic herbicide, namely, 2-(2,4-dichlorophenoxy)-propionic acid, were prepared by the concentrated emulsion polymerization method. A mixture of styrene, herbicide, and initiator was dispersed into a small amount of water (6% by volume based on the entire emulsion) containing surfactant, at room temperature. The heating at 40°C of the foam like gel thus obtained led to the formation of latexes containing the herbicide. It was found that the model herbicide dispersed in the polymer latex was released to water over a period of several weeks and that the amount released was strongly dependent upon temperature and latex concentration in water.

INTRODUCTION

The controlled release technology has recently received widespread attention because of its high efficiency in the use of active chemicals, such as drugs, pesticides, or fertilizers, without the need of multiple application.¹⁻³ One of the methods to achieve controlled release is the physical incorporation of the bioactive agent into an inert matrix by encapsulation, blending, or embedding. The molecular diffusion of the active agent in the matrix is generally controlling the release rate. Although natural or synthetic polymers have been widely utilized as vehicles for bioactive agents,¹⁻³ no investigation has yet been reported in which polymer latexes of submicron size were employed as inert media. The colloidal size of such a vehicle and the possible stabilization of the colloidal dispersions in aqueous environments could allow the polymer latexes to become valuable candidates for various controlled release applications where hydrophobic active agents are released into hydrophilic environments. However, when the solubility of the active agent in water is not small, neither the conventional emulsion polymerization, in which polymerization takes place in micelles, nor the miniemulsion polymerization,⁴ in which polymerization occurs in the monomer droplets, are appropriate procedures for the preparation of polymer latexes containing active ingredients. In both systems, the ratio of the volumes of water to monomer is large and, therefore, a significant amount of the active compound escapes from the monomer phase to the water phase. In the conventional emulsion polymerization, there is an additional, more important, negative factor since polymerization occurs in the

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micelles and hence both the monomer and the active agent have to migrate from the monomer droplets to the micelles. In contrast, in concentrated emulsion polymerization,⁵ a very small amount of water, which can be smaller than 1% (based on the entire emulsion), is required to prepare a foam like emulsion (gel) and the polymerization occurs in the monomer droplets. The stability of this gel is ensured by the adsorption of a surfactant, which is dissolved initially in the continuous phase, on the interface between the network of thin liquid films of the continuous phase and the polyhedral drops of the dispersed phase. An efficient loading of the active agent in the polymer latexes thus becomes possible, since the amount of active agent dissolved in the water phase is very small.

In this paper, we report the preparation of polymer latexes containing a model herbicide, namely, 2-(2,4-dichlorophenoxy)-propionic acid, (2,4-DP), by the concentrated emulsion polymerization method, as well as the results obtained concerning the release behavior in water of these latexes. The solubility of this compound in water is very low (350 ppm at 20°C⁶). In this case, the miniemulsion method may also be appropriate for preparing latexes containing 2,4-DP. It is found that polymerization proceeds without a chain transfer process between the growing polymer radical and model herbicide, leading to the formation of latexes of 0.32 μm average diameter. The herbicide is released from the latexes over a period of several weeks with an amount released that strongly depends upon temperature and amount of water.

EXPERIMENTAL

Styrene (Aldrich) was distilled and Azobisisobutyronitrile (AIBN, Alfa) was recrystallized from methanol. Sodium dodecylsulfate (Aldrich) and 2-(2,4-dichlorophenoxy)-propionic acid (2,4-DP, Sigma) were used as received. Water was deionized and distilled.

A small amount of water (2.5 mL) containing sodium dodecylsulfate (0.4 g) was placed in a single neck flask of 100 mL capacity equipped with a mechanical stirrer. Styrene (36 g) in which 2,4-DP (2.67 g) and AIBN (0.27 g) were dissolved by heating at 40°C was added dropwise to the stirred aqueous solution through an addition funnel, at room temperature. A gel-like emulsion is thus generated, where the dispersed monomer phase is composed of cells separated among them by thin films of water. The concentrated emulsions thus prepared were transferred to centrifuge tubes (15 mL capacity), which were then sealed with rubber septa. A mild centrifugation was employed to achieve better packing of the polyhedral drops. Polymerization was carried out at 40°C in the presence of air. It is difficult to disperse the latexes in water when polymerization approaches completion because they agglomerate. Therefore, additional water (typically twice as much as the initial weight of the emulsion) was added into the tubes when the conversion reached about 50% (after about 22 h). During polymerization, a small fraction of the cells of the gel collapsed and formed a bulk monomer phase in which bulk polymerization occurred. The undispersed polymer was removed by filtration through a coarse filtering funnel. The filtered aqueous solution was further polymerized. After complete conversion, the concentration of the latexes in water was

measured by weighing the polymer after filtering through a fine membrane (0.1 μm porosity).

The molecular weight of the polymer and its distribution were determined by employing a GPC composed of 500, 10^4 , 10^5 , and 10^6 Å pore size columns (Waters, Ultrastyrigel) in series. Methylene chloride was used as the mobile phase and the flow rate was 1 mL/min. The GPC was calibrated using monodisperse polystyrene standards (Polymer Laboratories, U.K.) of molecular weight 10,000–12,000,000. For the GPC measurements, the aqueous latex solution was poured into methanol and the precipitated polymer was collected, dried, and dissolved in chloroform. The latter solution was injected into the mobile phase.

The polymer latexes were examined with a JEOL 100U transmission electron microscope. Copper grids coated with carbon films were used as substrates and dilute latex solutions (approximately 1×10^{-6} g/mL) were deposited on the substrates.

For the release investigations, the latexes dispersed in water were kept in a constant temperature bath and aliquots of the sample were taken after various lengths of time. The release experiments were conducted by measuring the concentration of 2,4-DP in water by HPLC. Polymer latexes were separated from water by filtering through a nitrocellulose membrane of 0.1 μm porosity (Microfiltration Systems), and the filtered aqueous solutions were injected into the HPLC. μ -Bondapak C_{18} and Shodex RSpak columns were connected in series and $\text{CH}_3\text{CN}/\text{water}$ (50/50 vol%) was used as the mobile phase. The wavelength of the detector was 278 nm and the retention volume for 2,4-DP was 3.2 mL at a flow rate of 0.8 mL/min.

RESULTS AND DISCUSSION

Preparation of Polystyrene Latexes Containing 2,4-DP

The polymerization of concentrated emulsions whose dispersed phase consisted of styrene and 2,4-DP was first investigated in order to study the effect of the active agent.

Figure 1 presents GPC curves for the polystyrene prepared by the concentrated emulsion method in the presence (curve b) and absence (curve a) of 2,4-DP. It also includes the GPC curve for the polystyrene prepared by the bulk polymerization method (curve c). The curves show that, with the addition of 2,4-DP to the dispersed phase, the molecular weight distribution broadens and the contribution of the molecular weights in the range between those produced in concentrated emulsions without 2,4-DP and those produced in bulk becomes significant. The data regarding polymerization in various conditions are summarized in table I.

As shown in Table 1, the percent conversion in concentrated emulsions decreases in the presence of 2,4-DP. The fraction of the cells of the foam that collapse during polymerization with the formation of a bulk monomer phase are comparable and relatively small in both cases. This indicates that the stability of the gel-like emulsion is not dramatically deteriorated by the presence of 2,4-DP.

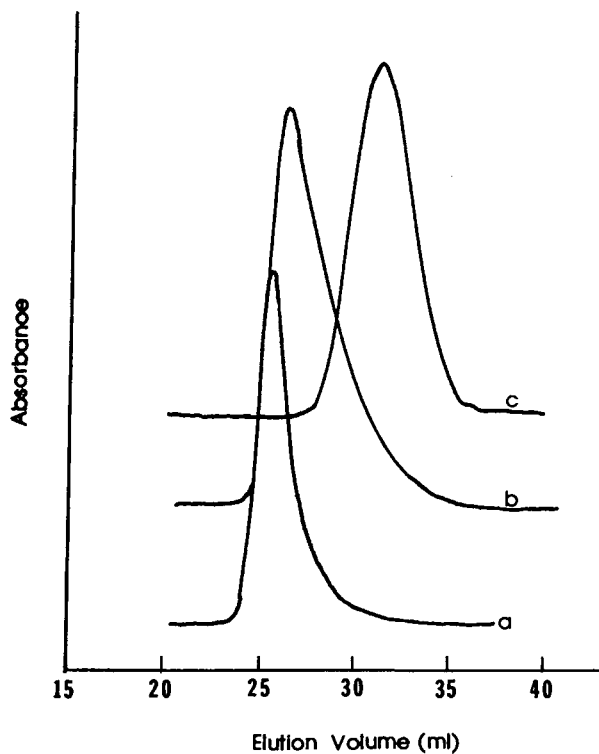


Fig. 1. GPC curves of polystyrenes produced at 40°C after 22 h of reaction: (a) prepared by concentrated emulsion polymerization; (b) prepared by concentrated emulsion polymerization in the presence of 6.9% 2,4-DP by weight to monomer; (c) prepared by bulk polymerization.

TABLE I
Polymerization of Styrene at 40°C for 22 h

	In concentrated emulsion	In concentrated emulsion with 6.9% 2,4-DP by weight to monomer	In bulk
Number average molecular weight	1.78×10^6	5.46×10^5	1.27×10^5
Weight average molecular weight	2.77×10^6	1.58×10^6	2.27×10^5
Polydispersity	1.56	2.89	1.79
Formation of bulk phase ^a	7.0%	8.1%	—
Polymer conversion (%)	75.4	53.8	15.2

^a Calculated by subtracting the areas under the following GPC curves: the GPC curve for the polymer formed both in the bulk and gel and the GPC curve for the polymer formed in gel.

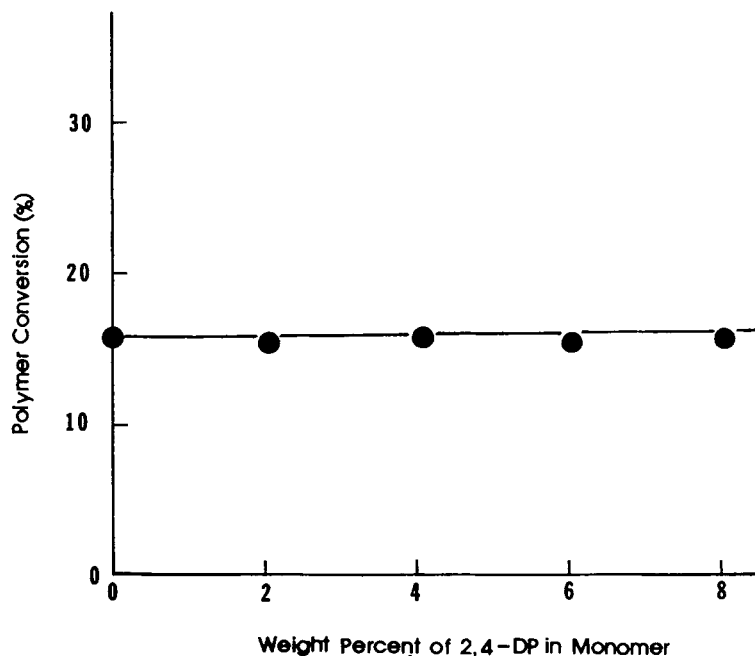


Fig. 2. A plot of conversion in bulk polymerization of styrene as a function of weight percent of 2,4-DP in the monomer (40°C, 22 h).

In order to understand the results of Table I, bulk polymerization was conducted in the presence of various amounts of 2,4-DP. Figure 2 is a plot of polymer conversion against the weight percent of 2,4-DP in the monomer phase and shows that the percent conversion is practically unaffected by the presence of 2,4-DP. The effect of 2,4-DP on the molecular weight of the resulting polymer was also investigated, and the corresponding GPC curves are presented in Figure 3. Despite the addition of a substantial amount of 2,4-DP, no appreciable difference between the two curves could be detected. Therefore, it is fair to conclude that no chain transfer occurs with the 2,4-DP during polymerization, since such a process would lower the molecular weight by the premature termination of the growing polymer radical. This is an important observation, since the chain-transfer process could result in the loss of active agent by its incorporation into the polymer.

Figure 4 presents transmission electron micrographs of the polymer latexes produced in the presence (b) and absence (a) of a herbicide in the dispersed phase. It is noticeable that the latexes containing 2,4-DP have a diameter of about 0.32 μm , which is significantly larger than those of the pure polystyrene latexes of 0.23 μm diameter. Perhaps the increase in the polarity of the dispersed phase in the presence of 2,4-DP leads to the formation of larger emulsion droplets because the interfacial free energy becomes smaller. In the previous paper,⁵ we suggested that the smaller mobility of the monomer in the cells of the gel, caused by the stiff nature of the emulsifier layer, may account for the enhancement in the polymer molecular weight and polymerization rate in concentrated emulsion polymerization as compared

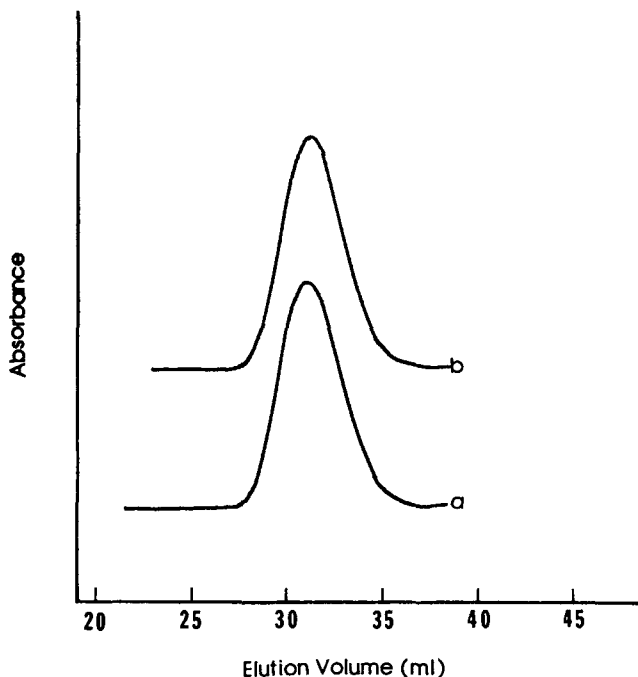


Fig. 3. GPC curves of the polystyrenes prepared by bulk polymerization (40°C, 22 h): (a) without 2,4-DP; (b) with 8% 2,4-DP by weight to monomer.

to polymerization in bulk. Accordingly, in the case of concentrated emulsion polymerization, the depression in the polymer molecular weight and percent conversion in the presence of 2,4-DP (Table I) may be due to a loss in rigidity in the monomer medium caused by the increase in the size of the emulsion droplet. Indeed, the influence of the emulsifier layer is expected to diminish as the emulsion droplet becomes larger.

Release of 2,4-DP in Water

The release behavior was studied with polystyrene latexes containing 6.9% 2,4-DP by weight based on the polymer. The highest loading with herbicide of the polystyrene latexes is limited by the solubility of 2,4-DP in styrene (which is 6.9% by weight).

When diluted with a sufficient amount of water (7.8×10^{-5} g/mL latex concentration) after 22 h of polymerization (the conversion is about 0.5), the polymer latexes released instantaneously half of the 2,4-DP embedded. It is likely that the looseness of the matrix due to unpolymerized monomer is responsible for this sudden, large initial release of active agent. It is, therefore, useful to examine the effect of the extent of polymerization on the initial release. Figure 5 plots the percent of 2,4-DP released immediately (about 5 min) on dilution against polymer conversion. No significant decrease in the initial release was detected until 80% conversion. The decrease in the initial "burst" becomes notable only when the conversion exceeds 85%. Accordingly, polymerization should be carried out close to completion in order to minimize

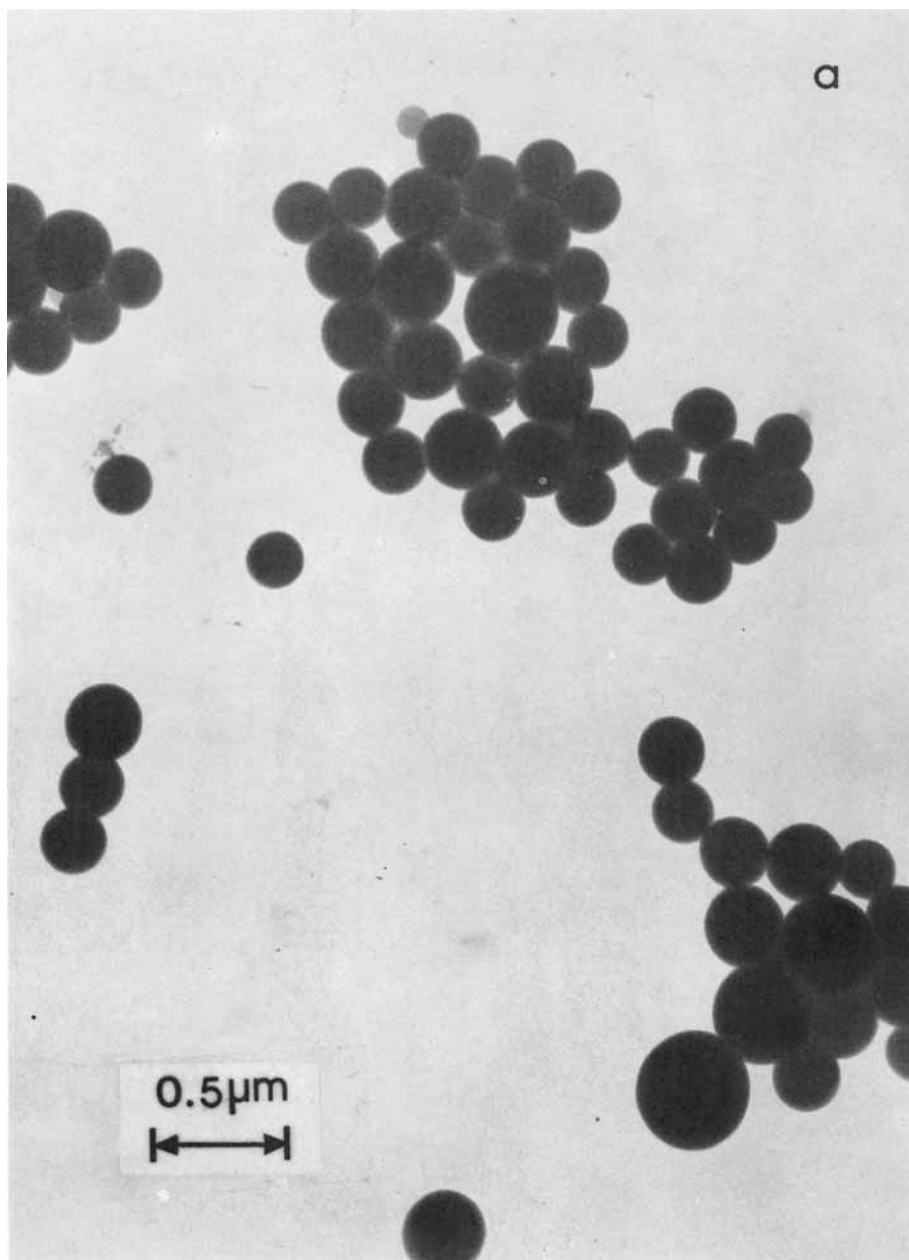


Fig. 4. Transmission electron micrographs of polymer latexes: (a) prepared without 2,4-DP; (b) prepared with 6.9% 2,4-DP by weight to monomer.

the loss of active agent on dilution. However, it should be noted that, in spite of high conversion, the latexes still released initially about 15% 2,4-DP when diluted with water (7.8×10^{-5} g/mL latex concentration). In order to clarify this observation, the initial instantaneous release when the latexes are diluted with various amounts of water was measured, and the results are plotted in

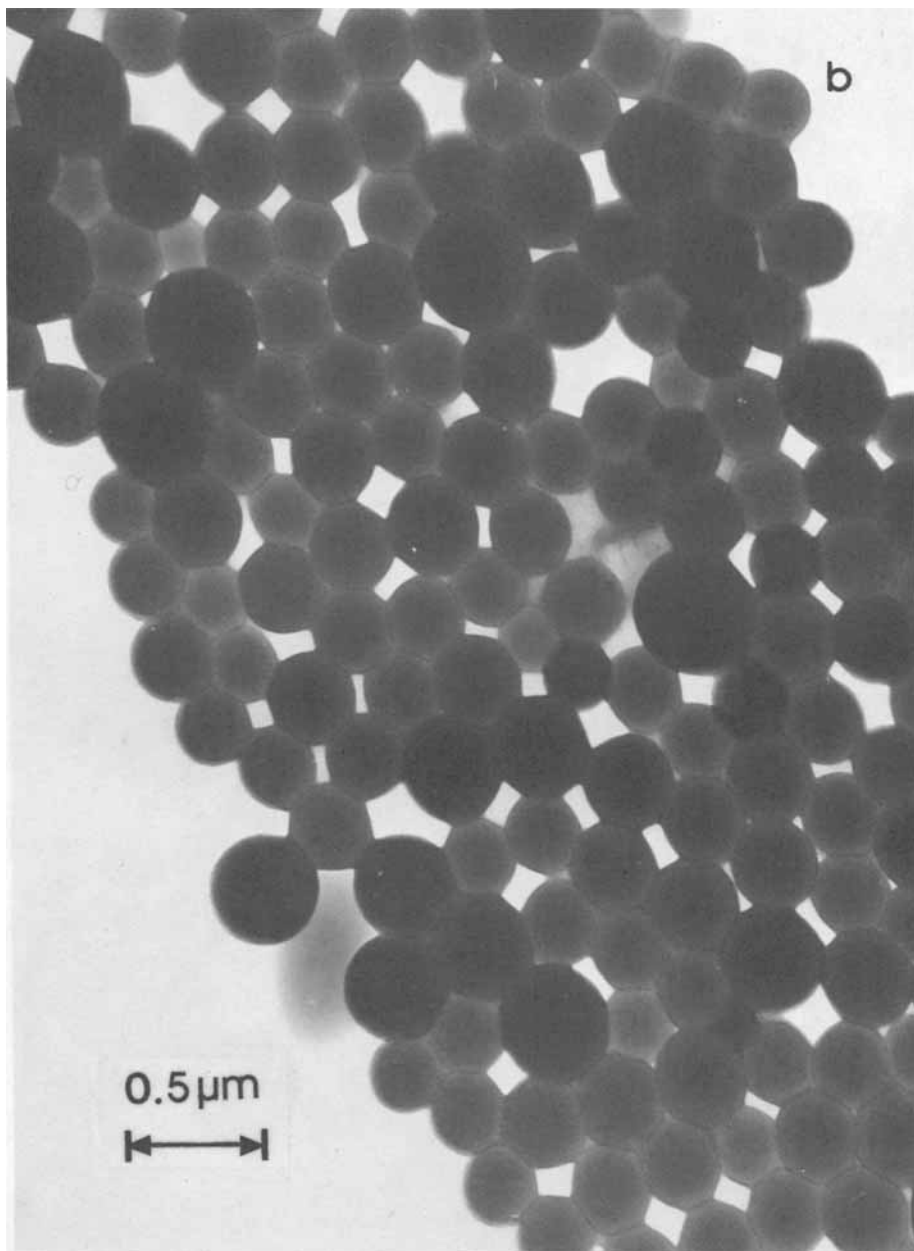


Fig. 4. (Continued from the previous page.)

Figure 6. The initial release increases with the amount of water until the latex concentration becomes 1.0×10^{-3} g/mL and remains constant for smaller values. This indicates that the dissolution of 2,4-DP located on the latex surface and/or in the vicinity of the latex surface is responsible for most of the initial release in Figure 5. The initial release would be independent of the amount of water used for dilution if it resulted solely from the escape of

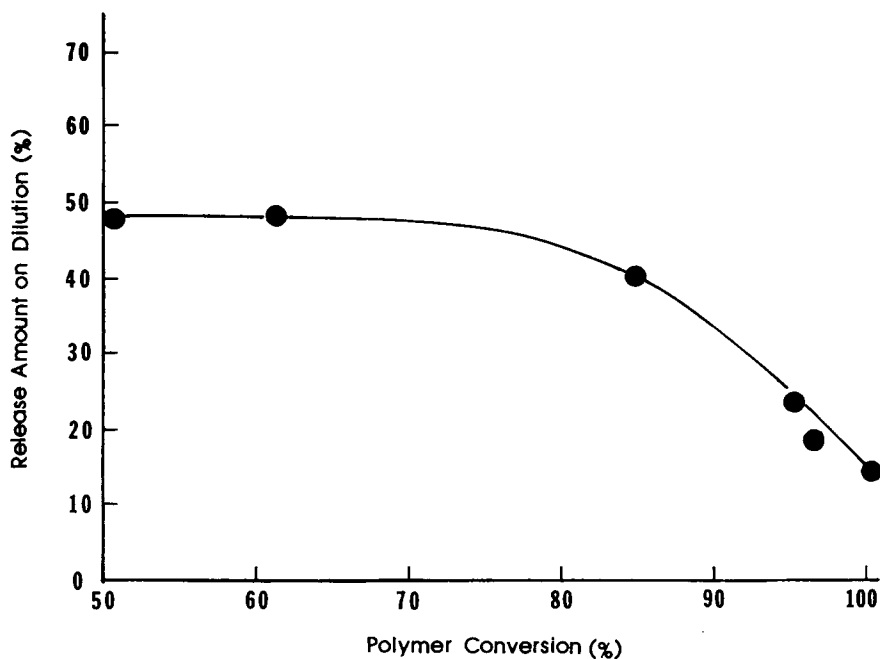


Fig. 5. A plot of the percent of 2,4-DP released on dilution as a function of conversion (latex concentration after dilution; 7.8×10^{-5} g/mL).

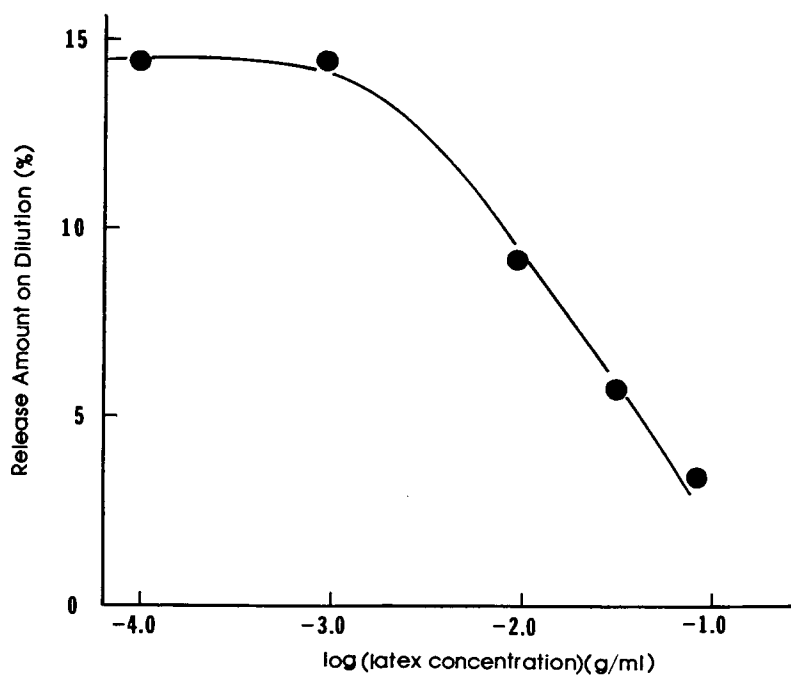


Fig. 6. Amount of 2,4-DP released on dilution with various amounts of water (the values in the abscissa signifies the latex concentrations after dilution).

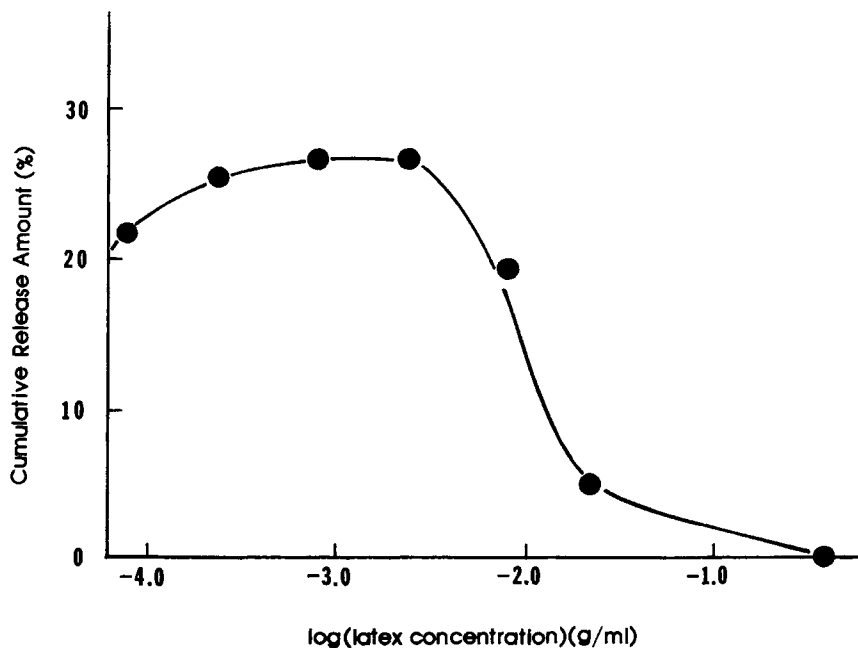


Fig. 7. A plot of the cumulative release percent of 2,4-DP as a function of latex concentration (22°C, 3 days; the release is plotted by excluding the initial release).

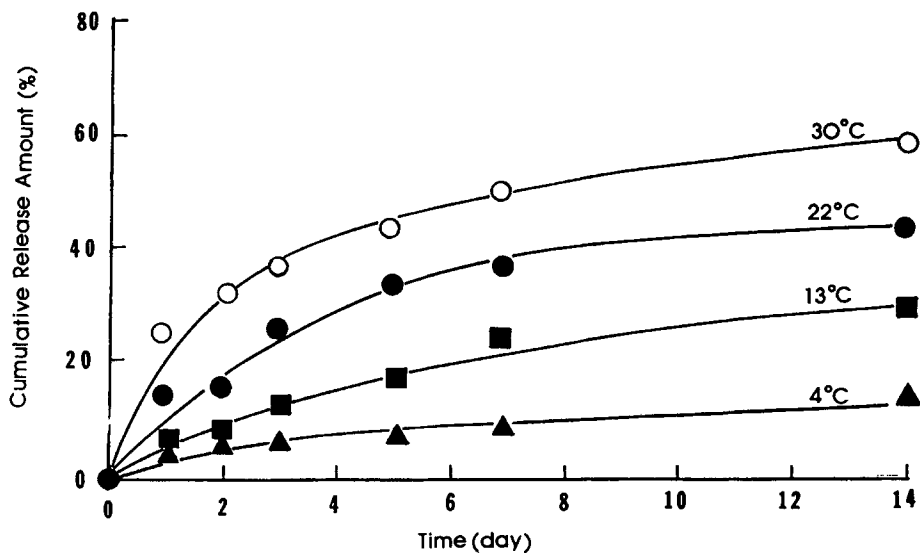


Fig. 8. A plot of the cumulative release percent of 2,4-DP as a function of time at various temperatures (7.8×10^{-5} g/mL latex concentration; the release is plotted by excluding the initial release).

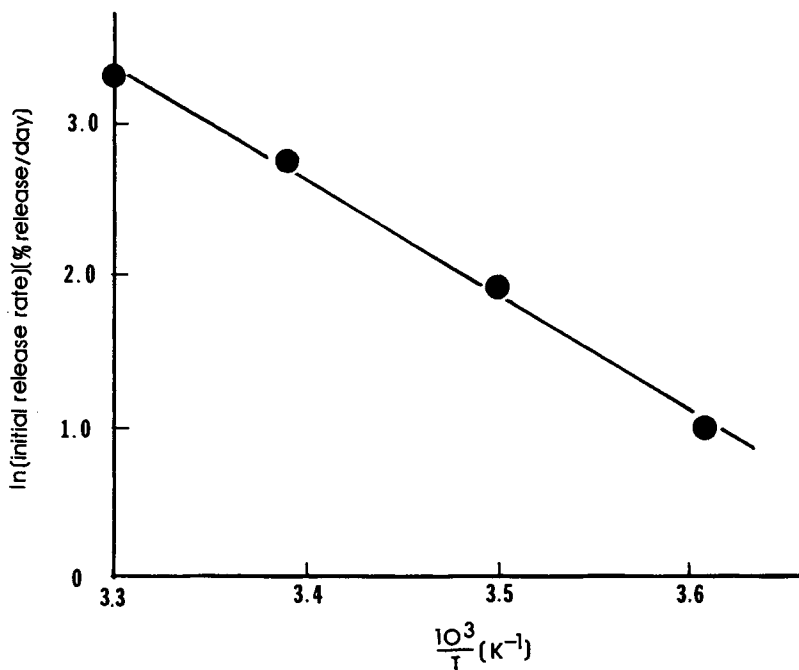


Fig. 9. Arrhenius plot for the initial release rate against temperature (the points have been calculated on the basis of Fig. 8).

2,4-DP from the monomer phase during the preparation of the concentrated emulsion.

Figure 7 shows the cumulative release of 2,4-DP after 3 days in a wide range of latex concentrations. As expected, the release is significantly inhibited at high latex concentrations because the amount of water available per particle is small. This is quite beneficial for practical applications since the premature release can be prevented by keeping the latex concentration large. While the decrease of the cumulative release with increasing particle concentration at sufficiently large values of the latter is understandable, since the amount of water becomes smaller, the occurrence of the weak maximum is less understandable. If real, it has probably a kinetic origin, the rate of dissolution being increased by the stirring produced by the Brownian motion of the particles. This may be important when the number of particles is sufficiently large but not too large to interfere with one another.

In Figure 8 the cumulative release of 2,4-DP is plotted against time at various temperatures. It shows that 2,4-DP is released from the polymer latexes into the aqueous medium over a period of several weeks. The cumulative amount released versus time is characterized by an initial steeper slope followed by an extended relatively flat region; the cumulative amount released is approximately proportional to the time at the power 1/2. The results of Figure 8 clearly demonstrate that the temperature plays a significant role on the release of 2,4-DP. For instance, only about 14% 2,4-DP is released at 4°C, while almost 60% 2,4-DP is released at 30°C after 2 weeks. The increased release at high temperatures is probably due to both the higher diffusivity of

the solute in the polymer matrix and to the enhanced solubility and diffusion of 2,4-DP in water.

The initial release rate against temperature can be described by an Arrhenius plot with an activation energy of 62.7 KJ/mol (Fig. 9).

CONCLUSION

The concentrated emulsion polymerization method can be used for the preparation of polymer latexes of submicron size in which active compounds are dispersed. Complete conversion is recommended in order to minimize the initial sudden release of active agent on dilution with water. The strong dependence of the release on temperature and amount of water suggests that the polymer latexes could be employed as valuable carriers in temperature and moisture sensitive release systems.

Dr. I. Sushumna has carried out the electron microscopy work.

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