Controlled Release of Perfumes from Polymers. II. Incorporation and Release of Essential Oils from Glassy Polymers

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ABSTRACT: Release of essential oils from glassy hydrophilic copolymers of 2-hydroxyethyl methacrylate (HEMA) and ethylene glycol dimethacrylate (EGDMA) was studied in a range of releasing media at 30°C. The release of carvone, limonene, and eugenol was investigated using swelling-controlled release systems based on these copolymers. By changing the crosslinking ratio of the copolymers it was possible to achieve zero-order release. The amount of essential oil release was correlated to the thermodynamic compatibility of the oil–polymer pair, as judged by the solubility parameter difference.
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Key words: swelling-controlled release systems; essential oil release; poly(2-hydroxyethyl methacrylate); carvone; limonene; eugenol

INTRODUCTION

Novel controlled release systems for applications as consumer products have been discussed by Brannon-Peppas.[1] Such systems include formulations for release of essential oils, perfumes, deodorants, moisturizers, and related active agents.[2–4] These devices may be in the form of microparticles, nanoparticles or emulsions, patches, disks, or even cylindrical sections. They may be required to release active agents for a period of 6 to 12 h, preferably at a constant rate (but also simply a sustained one) and in contact with moisture or the skin.

The incorporation of fragrances in polymers for the purpose of controlled release over a period of 12 or more hours has been a subject of significant research in recent years. Direct application of the main theories of controlled release can lead to novel formulations with desirable rates.[4] Perfumes are mixtures consisting of essential oils and other substances. Their incorporation in polymers (especially in microemulsions) could lead to new and innovative products for prolonged delivery of these substances.[5]

In a previous contribution to this series,[6] we analyzed the incorporation of essential oils in a wide range of hydrophilic polymers and copolymers and presented novel methods for determining the essential oil partitioning between the polymer carrier and the surrounding fluid. Such effects have been further analyzed in our work with Bindschaedler et al.,[7] in which we concentrated on active agent distribution in polymer microparticles.

The requirements and special characteristics of essential oil release systems render swelling-controlled release systems[8] highly desirable devices for such applications. In fact, various such devices have been patented or used for commer-

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cial development of a wide range of consumer products, including space air fresheners, space deodorants,[9] or even pH-triggered devices for fragrance release in contact with the skin.[1] For example, Dross[10] reported the use of initially dry crosslinked poly(2-hydroxyethyl methacrylate) (PHEMA) for the release of various fragrances, whereas early studies[11] reported the use of the same crosslinked polymer but swollen in the presence of silicone. This latter system was reported to have been able to release anethole, menthol, and other essential oils.

Release from such hydrophilic, swellable polymers is preferred because the release rate can be controlled by the structure of the polymers. Contrary to what might occur with encapsulated products containing essential oils, failure of the polymer carrier (e.g., through the formation of pinholes or a crack) does not lead to immediate release of all the active agent. Although the literature contains numerous examples of possible formulations prepared or recommended for specific consumer applications (for a detailed patent literature presentation, consult refs. 1–5), unfortunately an unexplainable scientific secrecy exists as to the specific details of the release behavior that precludes any serious mechanistic analysis of the release of volatile ingredients such as essential oils.

Probably the only detailed and accurate analysis of essential oil release from polymers available in the public domain is the study of limonene desorption from polypropylene reported by Moaddeb and Koros.[12] In that study, limonene desorption was followed as a function of time and analyzed by Fickian or non-Fickian diffusion.

In this article, we report on experimentation with a simple hydrophilic material, a copolymer of monofunctional 2-hydroxyethyl methacrylate (HEMA) and difunctional ethylene glycol dimethacrylate (EGDMA), where the latter also acted as a crosslinking agent. This copolymer will henceforth be designated as P(HEMA-*co*-EGDMA). Owing to the relatively small molecular size of all essential oils tested, and to yield meaningful long-time release rates (over a period of at least 8 h), we used the crosslinking agent EGDMA at levels of at least 1 mol % to obtain dense networks.[13]

The release behavior was followed by gas chromatography, and the results were analyzed by Fickian and non-Fickian expressions, as discussed by Ritger and Peppas.[14]

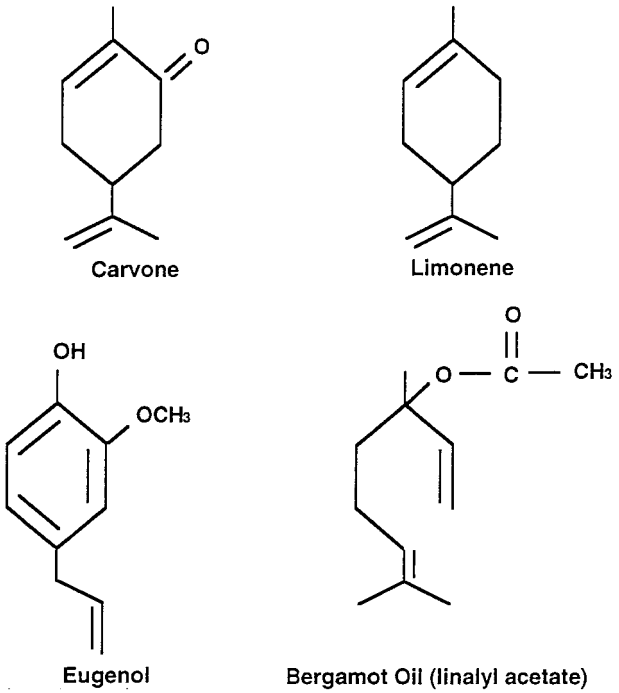

Figure 1 Chemical formulae of essential oils employed.

EXPERIMENTAL

Glassy polymer disks were prepared by reacting vacuum-distilled HEMA (Polysciences, Inc., Warrington, Pennsylvania) with EGDMA (Polysciences) at nominal crosslinking ratios of $X = 0.001$, 0.010, and 0.050 mol EGDMA/mol HEMA. The reaction was initiated by 0.1 wt % azobis isobutyronitrile (AIBN) and carried out in polypropylene vials at 70 ± 1°C for 24 h.

Three essential oils and one mixture were employed in these studies and were loaded either by mixing with the monomers during the polymerization process or by imbibition of the ensuring polymers from 5 vol % ethanolic solutions. Carvone or *p*-menthe-6,8-dien-2-one (oil of spearmint, MW = 150.22), limonene or 1-methyl-4-isopropyl-1-cyclohexene (oil of lemon, MW = 136.24), and eugenol or 4-ally-2-methoxyphenol (oil of cloves, MW = 164.2) were supplied by Gattefossé S.A., St. Priest, France, and used as received. Bergamot oil consisting of a mixture containing linalyl acetate or 3,7-dimethyl-1,6-octadien-3-yl acetate (oil of citrus, MW = 196.29) as a main component was obtained from Gattefossé S.A., St. Priest, France. The chemical formulae of these compounds are summarized in Figure 1.

In a typical experiment, cylinders of known

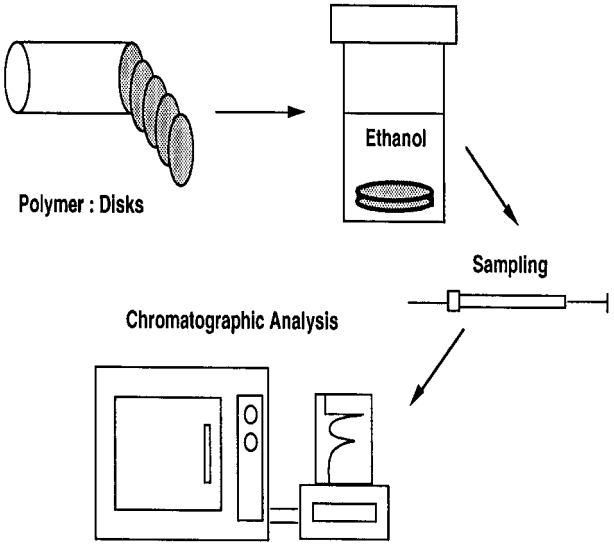

Figure 2 Experimental study of essential oil release.

nominal crosslinking ratio were prepared by free-radical, bulk copolymerization of HEMA and EGDMA for 24 h, a time sufficient for complete reaction.[15] The resulting cylinders were cut with a rotary knife in thin disks having a 0.7-cm diameter and an average thickness of 0.9 mm (on a dry basis). In a typical imbibition experiment, essential oil was loaded by dissolving it in a 5 vol % ethanol solution and allowing a single disk to absorb the active agent up to equilibrium for a period of up to 7 days at room temperature (Fig. 2). For example, in disks with crosslinking ratio X = 0.001 mol EGDMA/mol HEMA, the equilibrium amount of eugenol was 2.9 wt %.

The alternative method of oil incorporation during reaction was used successfully for some of the active agents. For example, it was possible to load up to 8.9 wt % eugenol in a crosslinked PHEMA sample with X = 0.01 mol EGDMA/mol HEMA.

Release studies of the active compounds were carried out in 50-ml vials containing ethanol at 30 ± 1°C. The active agent concentration was determined by gas chromatography with a flame ionization detector (Model 3700, Varian, Palo Alto, California) equipped with an integrator (HP3396, Hewlett–Packard). Using a Hamilton microliter syringe, samples were taken every 2 min and analyzed using 280°C as the injector and detector temperatures and 190°C as the isothermal oven temperature (for eugenol). A Carbowax column of 15 m × 0.53 mm with splitless injection was used with helium as a carrier gas at 3 ml/min. The results were calibrated with standard solutions of 1, 2, 3, and 5 wt % of active compound in ethanol.

RESULTS AND DISCUSSION

Using the reaction or imbibition process it was possible to load up to 9.6% essential oil in dry, crosslinked P(HEMA-*co*-EGDMA) polymer disks. Differential scanning calorimetry indicated that in all cases the glass transition temperature of these samples (controlled release systems) was higher than 56°C. Thus, at room temperature release occurred from initially glassy polymer films.

Figure 3 shows typical release profiles of carvone, eugenol, and bergamot oil from P(HEMA-*co*-EGDMA) disks in ethanol at 30°C. These disks were crosslinked at a relatively high level of 5 mol % (X = 0.05). Carvone, with a low molecular weight and a more hydrophilic chemical structure, was released faster from these disks. Complete release of all the incorporated agent was achieved in 9 h. The dynamic release of this compound was obtained by plotting the data according to eq. (1)

$$\frac{M_t}{M_\infty} = kt^n \qquad (1)$$

Here, M_t/M_∞ is the fractional oil release, t is the release time, n is the diffusional exponent,[14] which is 0.5 for Fickian diffusion and 1.0 for relaxation-controlled Case-III transport,[14] and k is the diffusional kinetic constant. For carvone release,

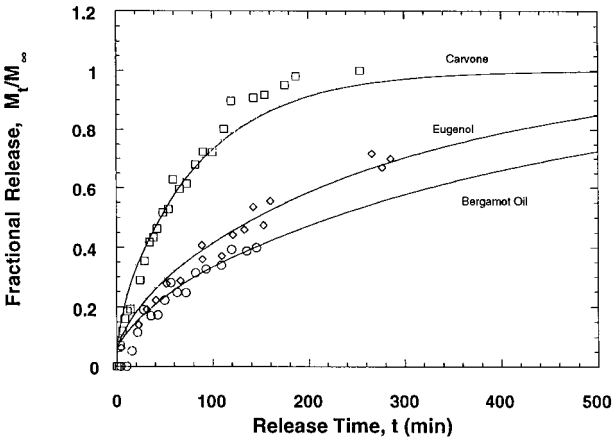

Figure 3 Fractional release of carvone (□), eugenol (◇), and bergamot oil (○) in ethanol at 30°C from crosslinked PHEMA disks containing X = 0.050 mol EGDMA/mol HEMA.

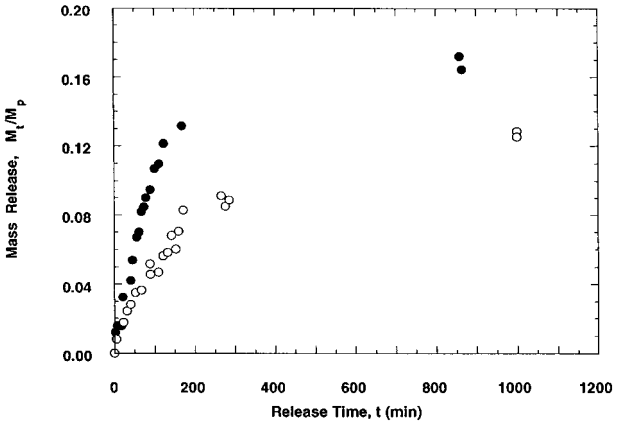

Figure 4 Release of eugenol per gram of dry polymer in ethanol at 30°C from crosslinked PHEMA disks containing X = 0.001 mol EGDMA/mol HEMA (●) or X = 0.050 (○).

the diffusional exponent was $n = 0.54 \pm 0.06$, indicating a diffusion-controlled release behavior.

Eugenol release was significantly slower. Complete release at 30°C was achieved after 13 h. Analysis of the dynamic behavior revealed a diffusional exponent of $n = 0.66 \pm 0.04$, indicating a transport mechanism with a chain relaxational contribution. Bergamot oil, a mixture of various oils, including linalyl acetate, is a very popular component in many products available in Mediterranean countries. Its release behavior in ethanol at 30°C was relaxation-controlled, with $n = 0.86 \pm 0.04$. Complete release was achieved in 23 h.

Clearly, this analysis indicates that these oil-containing delivery systems function as swelling-controlled release devices and allow the active ingredient to be released by a combination of classical diffusion and chain relaxation. The degree of crosslinking (as denoted by the crosslinking agent X) and the associated HEMA: EGDMA comonomer feed ratio are important parameters that can control the release rate and the release mechanism. For example, Figure 4 shows the release behavior of eugenol in ethanol at 30°C from P(HEMA-*co*-EGDMA) disks with 0.1 and 5 mol % crosslinking agents. Here the results are presented as eugenol released per mass of polymer film versus time. The initial release rate from the loosely crosslinked system was 9.5×10^{-4} g eugenol/g polymer min, whereas the release rate from the densely crosslinked system was 3.2×10^{-4} g eugenol/g polymer min. Both rates were calculated by fitting the initial dynamic swelling data to eq. (1) and taking the derivative as time approached zero. From the same analysis, the diffusional exponents were calculated as 0.96 ± 0.04 and 0.66 ± 0.04, respectively. Clearly, samples with the 0.1 mol % crosslinking agent provided the right relaxational characteristics for a zero-order release behavior.

Of the various essential oils tested, limonene was the most compatible with the polymer studied here. Figure 5 shows the normalized release of limonene in ethanol at 30°C. Analysis of these data gave a diffusional exponent of $n = 1.02 \pm 0.02$, indicating again a zero-order release behavior with complete release achieved at 5 h. Previously, Moaddeb and Koros[12] conducted desorption studies of limonene from polypropylene films at 30°C and estimated diffusional exponents of 1.03 at 100% activity (pure liquid).

The data analyzed thus far indicate that zero-order release of certain essential oils can be achieved from thin films of EGDMA-crosslinked PHEMA at 30°C. To achieve zero-order release (n = 1.00), one must try to work with polymer films that have relatively low crosslinking ratios (in order to achieve significant chain relaxation and coupling with essential oil diffusion). In addition, good compatibility of the essential oil with the polymer will provide maximum partitioning of the oil during release.

Additional studies of the compatibility characteristics of these systems[6] were obtained by comparing the solubility parameters of all components[16] tested at 30°C. The crosslinked polymer P(HEMA-*co*-EGDMA) had a solubility parameter[17] of $\delta_2 = 8.4$ (cal/cm^3)$^{1/2}$, whereas the four oils tested had solubility parameters of $\delta_1 = 8.1$ (limonene), 9.3 (carvone), 11.4 (eugenol), and

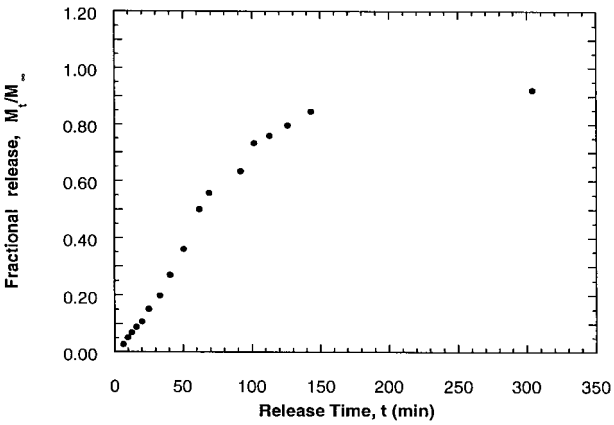

Figure 5 Fractional limonene release in ethanol at 30°C from crosslinked PHEMA disks with X = 0.050 mol EGDMA/mol HEMA.

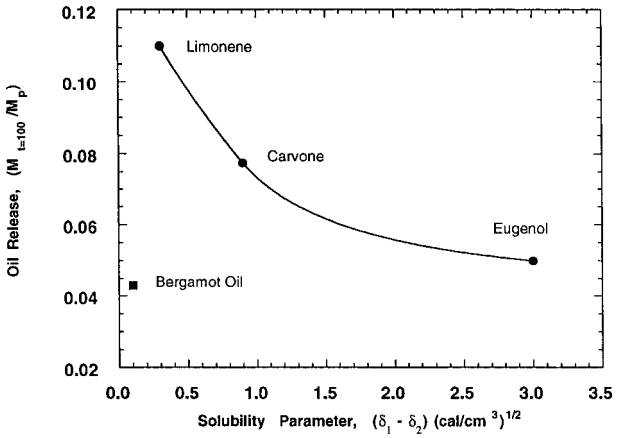

Figure 6 Essential oil release at t = 100 min/g of dry polymer as a function of the solubility parameter difference, $\delta_1 - \delta_2$, between essential oil and polymer.

8.3 (for linalyl acetate, the main component of bergamot oil). As is well known, maximum compatibility is achieved when the solubility parameter difference $\delta_1 - \delta_2$ is close to zero.[18]

Figure 6 plots the essential oil released at 100 min per gram of dry polymer versus the difference $\delta_1 - \delta_2$. Clearly, a correlation can be established between release rate and compatibility. The data for bergamot oil are not superimposed because this substance is a mixture of oils. Thus, compatibility is an important factor in the release process of essential oils from glassy polymers.

CONCLUSIONS

We have demonstrated that release of fragrances from PHEMA-based polymers is dependent on the temperature, crosslinking ratio, solubility parameter, and chemical structure. Release of essential oils from PHEMA-based polymers can be zero-order if the crosslinking ratio is kept at a low level, probably less than 1 mol %, and the compatibility with the polymer is maximized.

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