Characterization of Dendritic Polymer-Modified Porous Silica Particles Using Size Exclusion Chromatography

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Dendritic polymer-modified porous silica particles prepared by poly(amidoamine) (PAMAM) dendrimer synthesis reaction were characterized by elementary analysis (EA) and size exclusion chromatography (SEC). EA demonstrated the successful alternate growth of dendritic layers on the particles. The phased growth of polymer moieties by cascade reactions filled pores on silica particle, and decreased M_{lim}s. It was found that the pore-size distribution can be controlled by the generation number and the reaction conditions.

Recently, the synthesis and application of hyper-branched polymers like dendrimers and starburst polymers have attracted much attention as a new class of polymer materials.[1–3] The cascade reactions for dendrimer synthesis can also be applied to surface modification.[3–5] Crooks and co-workers have reported the electrochemical applications of dendrimer modified electrodes.[3] Synthesis of dendritic polymer-modified particles started from a silica surface have been reported by Tsubokawa and co-workers.[4] Furthermore, Bourque and co-workers studied the catalytic hydroformylation reaction using dendritic polymer-modified silica with rhodium-complex.[5] Modified particles with a hyper-branched structure are also attractive for high-performance liquid chromatography (HPLC) as a packing gel. The application of hyper-branched polymer modified particles for chromatography has already been reported.[6] In this letter, we would like to report the characterization of dendritic polymer-modified porous silica particles by SEC, as a preliminary approach to the designed modification of HPLC gels using cascade reactions.

An alternate reaction between methyl acrylate (MA) and ethylenediamine (EDA), which form the PAMAM dendrimer, was used for this synthesis.[1] In order to introduce primary amino groups onto the silica surface, the porous silica particles (spherical Silica Gel 60, Kanto Chemical Co., Inc. Japan) was treated with 3-aminopropyl triethoxysilane in toluene at reflux. The zero, n + 0.5th and n + 1th generations indicate aminated, ester terminated and amine terminated silica particles after nth times of the repeated dendrimer synthesis reaction, respectively. The diameter and pore size of the silica particles were 40–100 μm and 55–75 Å, respectively. The aminated silica particles were further reacted with 2M MA (n + 0.5th generation reaction) and 7.5 M EDA (n + 1th generation reaction) for the same length of times varying from 1 to 48 h in methanol at 25 °C alternately. The modified particles were very easily purified by washing with methanol over a suction glass filter. The particles were confirmed by elementary analysis. Figure 1 shows the typical changes in the grafting ratio and the C%/N% ratio of the dendritic polymer-modified particles based on the number of reaction cycles. The grafting ratio is defined in equations (1) and (2); it corresponds roughly to the ratio of the number of modified polymer moieties on the silica over the number of silica core moieties.

$$\mathrm{sum}\% = \mathrm{H}\% + \mathrm{C}\% + \mathrm{N}\% \tag{1}$$
$$\text{Grafting ratio} = \mathrm{sum}\% / (100 - \mathrm{sum}\%) \tag{2}$$

The grafting ratio increased with successive repeats of the reaction. The increases in the grafting ratios gradually decreased, but did not saturated by the 5th generation. The grafting ratio can also be controlled by the reaction time. The grafting ratios of dendritic polymer-modified silica particles reacted for 1, 10, 24, 48 or 120 h for the 5th generation were obtained as 0.29, 0.48, 0.61, 0.72 and 0.74, respectively. The grafting ratio did not change much after 48 h. In general, the increases in the grafting ratio gradually decreased with the number of reaction cycles. This indicates that the dendrimer synthesis reaction on the surface is not a complete one. The dendritic moieties on the silica obviously included some non-reacted residues, which remained as primary or secondary amino groups. This might be due to the steric hindrance of the hyper-branched structure, as well as the immature termination of the reactions in the pores of the porous silica. Tsubokawa pointed out that the modified particles were more likely to have a highly branched polymer rather than a true dendrimer, especially at higher generations.[5]

The zigzag lines of the C/N ratio in Figure 1 clearly show the alternate introduction of MA and EDA. The introduction of MA resulted in the increased C content and C/N ratio at n+0.5th

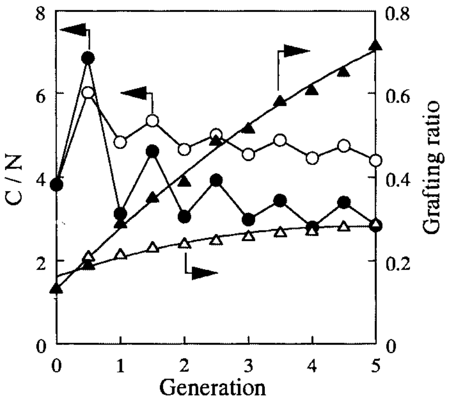

Figure 1 Changes in the C/N ratios (circles) and grafting ratios (triangles) plotted against the generation for modified particles reacted for 1 (open) and 48 (solid) h.

generation. On the other hand, the reactions with EDA give rise to an increased N content, and thus a decrease in the C/N ratio was observed at the n + 1th generation. Interestingly, the rise and drop cycle of C/N ratio, due to the alternate introduction of MA and EDA, was observed even for the 1-h reacted particles of over 4th generation. This proves that the shortest reaction time still allows for the alternate modification to proceed successively, even though the grafting ratio seemed to be almost saturated.

SEC techniques have been frequently used for the purification and size evaluation of dendrimer.[1] However, we used SEC techniques to evaluate the properties of dendritic polymer-modified porous silica particles as a stationary phase for HPLC.[7] The porosity of the stationary phase directly affects the properties and separation characteristics on HPLC. To our knowledge, this is the first report of this novel approach to the chromatographic applications of dendritic polymer-modified particles.

Degassed aqueous slurries of the particles were packed into a column (15 × 0.46 cm i.d.). The SEC experiments were conducted in an aqueous eluant using homologous pullulans, maltoheptaose, maltohexaose, maltotriose, maltose, glucose and D_2O as standard samples. Figure 2 shows the typical aqueous SEC calibration curves for an aminated porous silica particle and for dendritic polymer-modified particles of the 5th generation. The SEC calibration curves of the above sugars reveal typical size exclusion behavior without any specific adsorption or partition.

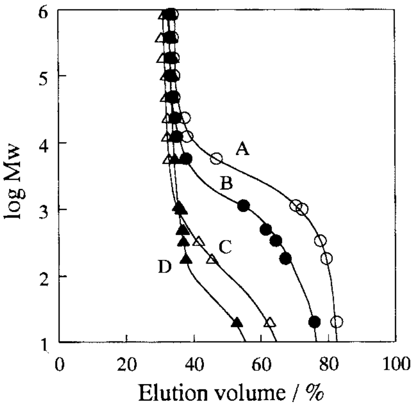

Figure 2 SEC curves for an aminated silica particle (A), and for dendritic polymer-modified silica particles (reaction time 1 h, B; 10 h, C; 48 h, D).

The distribution of the pore-size of the dendritic polymer-modified spheres was estimated by the exclusion molecular weight (M_{lim}), which was determined by extrapolating the linear part of the calibration curve.[7] The pore-size distribution was notably affected by the grafting ratio; the pore size decreased with the increased grafting of dendritic moieties moderated not only by the generation, but also by the reaction time. The phased growth of polymer moieties by cascade reactions filled pores on silica particle, and decreased M_{lim}s depended on grafting ratios. The M_{lim} for an aminated porous silica was 16000. When the reaction was conducted for 1 h, the modified particle of the 1st generation showed a decrease in the M_{lim} to ca. 8000. However, the M_{lim} remained almost constant after the successive cascade reactions. On the other hand, the M_{lim} value decreased continuously with increasing generations in the case of particles reacted for 48 h. The M_{lim} for dendritic polymer-modified particles of the 5th generation, which were reacted for 1 or 10 h, was 7800 and 1500, respectively. Surprisingly, the particles reacted for 48 h excluded all sugars, including even the smallest sugars such as glucose, except for D_2O. The lowest M_{lim} of the particles reacted for 48 h ($20 < M_{lim} < 180$) indicates that the micro-pores on the silica surface were completely filled, and that the modified dendritic layers were densely packed. All results clearly show that the pore distribution can be controlled by the reaction conditions and the stepwise cascade reaction allows to control overall pore distribution of modified particles.

In conclusion, we successfully demonstrated in the first chromatographic application of dendritic polymer-modified particles. The combination of such stepwise modification based on cascade reaction and the introduction of ligand moieties will lead to the designable gel packings not only for SEC but also for multi-separation modes, SEC and other separation mode such as partition, adsorption and ion-exchange.

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