

Concentrated Emulsion Polymerization for Preparation of β -Cyclodextrin-Supported Chromatography Columns

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ABSTRACT: Concentrated inverse emulsion polymerization was used for making chromatography columns (based on crosslinked polystyrene divinylbenzene (PS-DVB)) with pore sizes less than 10 μm . According to DSC-thermal gravimetry thermograms, it was confirmed that the residual monomer concentration after polymerization process is negligible. For application of these columns in chiral chromatography, the β -cyclodextrin is chemically fixed on the PS-DVB resin pore surface. The presence of hydroxyl groups in the PS-DVB resin after chemical modification was confirmed by FTIR spectroscopy. By chemical modification of

the PS-DVB resin, thermal stability increased up to 446°C. The structure of columns was analyzed by scanning electron microscopy (SEM). SEM evaluations showed that the porous structure of PS-DVB resin was maintained intact after the chemical modification with β -cyclodextrin. According to X-ray data, presence of the crystalline domain that is related to β -cyclodextrin is confirmed. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 102: 857–863, 2006

Key words: inverse concentrated emulsion polymerization; styrene; β -cyclodextrin; latices

INTRODUCTION

Cyclodextrins (CDs) are cyclic oligosaccharides consisting of 6, 7, and 8 glucose units (α -, β -, and γ -CD) joined by α -1,4-glycosidic linkages. CDs resemble a hollow, truncated cone, with primary hydroxyl groups located on the narrow rim of the cone and secondary hydroxyl groups on wide rim of the cone. The hydroxyl groups located on the exterior of the cone makes CDs hydrophilic and soluble in aqueous solutions, but the interior cavities of CDs are hydrophobic, allowing CDs to incorporate small molecules or guests to form host–guest inclusion complexes (ICs). CD ICs have been made with various drugs, perfumes, and flavorings. The ability of CDs to complex with a considerable variety of molecules has been well documented. Crystallographic data as well as computer-generated molecules modeling based on minimum free energy calculations provide evidence for preferential enantiomeric IC formation. Indeed, these versatile molecules have been used extensively in synthesis and separation alone or bonded to a support (polymeric or non polymeric supports).^{1–8}

In contrast to the conventional emulsions, concentrated emulsions have a large volume fraction of dispersed phase, greater than 0.74 and as large as 0.99. It has a paste-like appearance and behavior. When

the volume fraction of the continuous phase is sufficiently small, the dispersed phase is composed of polyhedral cells separated by thin films of continuous phase. The concentrated emulsions are prepared by dropwise addition of the dispersed phase to a small amount of a continuous phase containing a surfactant. The concentrated emulsions have attracted our attention as a possible pathway for polymerization for a number of reasons:

1. The ordered organization of surfactant molecules at the interface between the two media may organize the monomers in its vicinity and thus accelerate the rate of conversion.
2. Because of the presence of the surfactant layer, the reduced mobility inside the cells could generate an earlier gel effect, which would lead to the delay in the bimolecular termination reaction. Hence, the higher molecular weight is expected to be higher if the polymerization occurs in a concentrated emulsion than in bulk.
3. The polymerized system maintains the structure of the emulsion precursor.
4. A better control of the size of latices can be made by controlling the size of the cells of concentrated emulsion, using suitable surfactants, ionic strengths, and pH values. Hence the splitting of a bulk system into a large number of small, independent cells may have favorable effects. In addition, a concentrated emulsion can be polymerized to generate either latices, a porous medium, or a composite.^{9–12}

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The aim of this research work was to prepare β -CD-supported chromatography columns by using the concentrated emulsion polymerization technique.

EXPERIMENTAL

Materials

The following chemicals were used: styrene (St; Merck), divinyl benzene (DVB; Merck), Span 80 (emulsifier; Merck), azobisisobutyronitrile (AIBN; Fluka), cummene hydroperoxide (Aldrich), β -CD (Merck), acrylic acid

(Ac), thionyl chloride (Merck), triethylamine (TEA; Merck), acetone (Merck), calcium hydride (Merck), dichloroethane, *N,N*-dimethylformamide (DMF; Merck).

Apparatus

Thermal analysis (DSC-thermal gravimetry (TG)) of resins was carried out on an STA 625 analyzer (Polymer Labs, Poole, UK) in N_2 at a heating rate of $10^\circ\text{C}/\text{min}$ to measure thermal stability and residual monomer concentration of the produced resins. X-ray diffractometer (XRD) measurements were performed using Siemens D5000 diffractometer. The porous structure of PS-DVB resins was studied using a scanning electron microscope (SEM; Cambridge Model S 360, Cambridge, UK).

TABLE I
Applied Formulations

Styrene (g)	10.75
DVB (g)	1.72
Span 80 (g)	1.34
AIBN (g)	0.07
Cummene hydroperoxide (g)	0.07
Water (g)	63

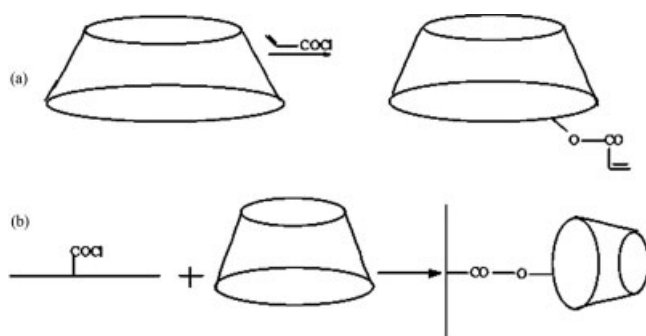


Figure 1 Schematic demonstration of the resin modification with CD.

Procedure for preparation of concentrated emulsion

A 250-cm^3 three-neck round-bottom flask was filled with a magnetic stirrer and thermometer. To prepare an inverse emulsion of water in monomer solution, the flask was initially charged with St, DVB, emulsifier, and initiators. Then double-distilled water was added dropwise to this solution, with continuous stirring. The concentrated emulsion containing 84% dispersed phase was prepared and transferred into glass tubes by means of vacuum. The packed tubes were closed and polymerization was performed in the oven for 48 h at 50°C . Then the water phase or dispersed phase of the PS-DVB resin was removed by drying. Considering the fact that at low percentage of crosslinking, the dimensional stability of chromatography column is low due to swelling with different solvents, by selecting 16% DVB as a crosslink-

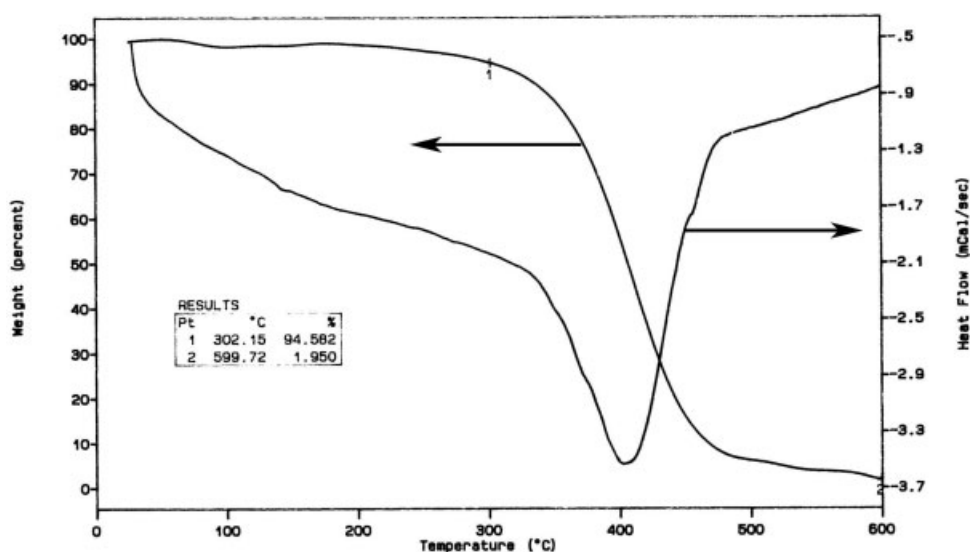


Figure 2 DSC-TG thermogram of PS/16%DVB, in N_2 , at heating rate of $10^\circ\text{C}/\text{min}$.

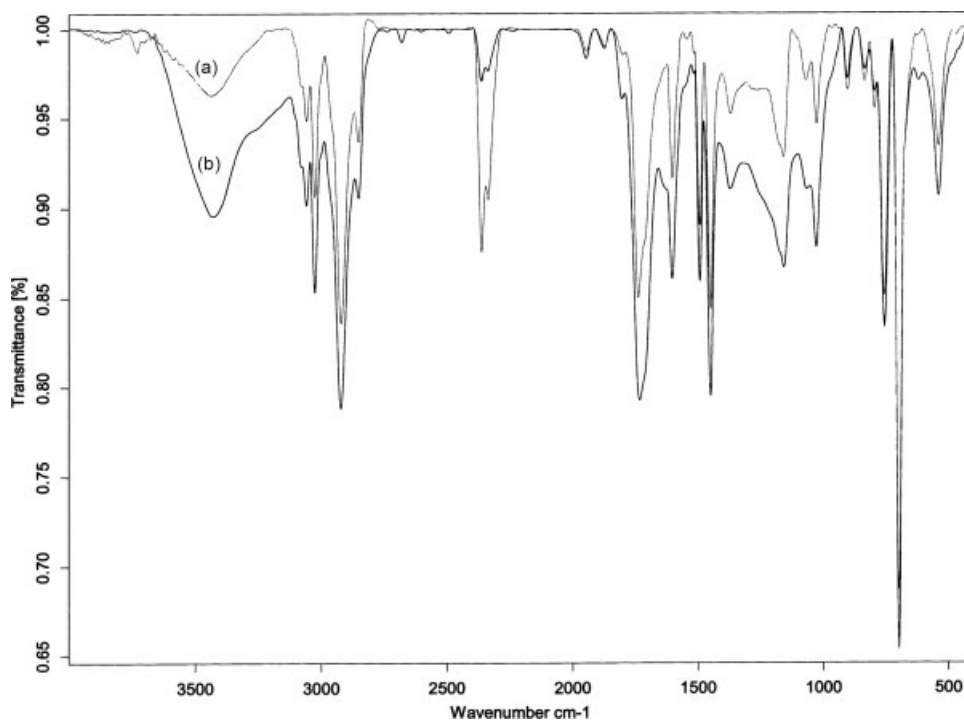


Figure 3 FTIR spectra of PS/16%DVB/Ac (a) and PS/16%DVB/β-CD (b).

ing agent, we reached proper degree of dimensional stability. Applied formulations are listed in Table I.

Prepared resin modification with β-CD

As it is demonstrated in Figure 1, CD-modified resin can be prepared by two methods:

- a. First CD is modified using a acid chloride with vinyl group and then is used with St and DVB

in resin preparation step. By this method, there is a possibility for inclusion polymerization of St and DVB in the molecular cavity of CD. Finally, this method will prevent forming IC by CD cavity. Considering this limitation, this method will not be used here.

- b. In the second method, after resin preparation with St and DVB, it will swell for proper time (at least 2 h) in the presence of DVB, initiator (AIBN), and solvent (toluene). Finally polymerization

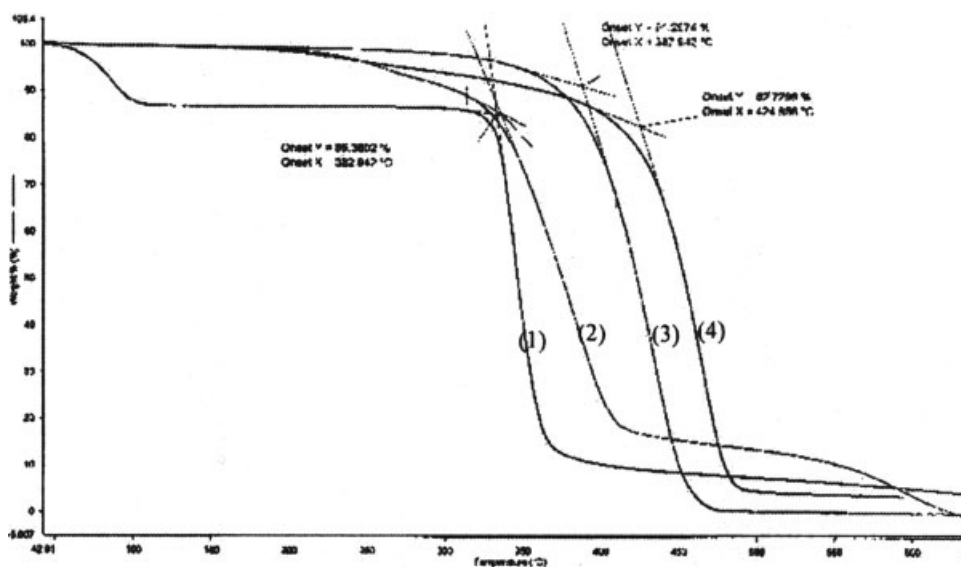


Figure 4 TG thermograms of β-CD (1), PS/16%DVB (2), PS/16%DVB/Ac (3), PS/16%DVB/β-CD (4).

TABLE II
Thermal Stability of Prepared Resins

Sample	Thermal stability (°C)
PS-16%DVB	335
PS-16%DVB/Ac	387
PS-16%DVB/ β -CD	424

takes place at 60°C for 24 h. After washing with solvent and drying at this condition, modified resin with carboxylic groups is prepared. Then these groups are converted to acid chloride using thionyl chloride. In this condition, modified resin with carboxylic groups is mixed with dry dichloroethane solution and required amount of thionyl chloride at 80°C for 2 h and then is dried under vacuum. After this stage, solution of β -CD in dry DMF and required amount of TEA are added to the modified resin at ambient temperature, and the mixture is kept under closed system for 48 h. After washing with DMF and drying, β -CD-modified resin is obtained.

RESULTS AND DISCUSSION

Considering the fact that the main purpose of synthesis of the modified resin is employing them as chromatography columns, they must have the following properties:

1. High thermal resistance
2. zero monomer residue in resin
3. maintenance of the porous structure

For thermal stability and residue monomer determination, TG-DSC thermal analyses were used. As it is seen in Figure 2 for samples with 16% DVB, TG thermogram almost remains constant up to degradation temperature. Absence of exothermic peak in DSC curve before degradation presents the absence of the residue monomer in the synthesized resin. Minor changes in TG thermogram before degradation point are due to the presence of solvent, water, and error in measurement device.

To verify the bonding of β -CD to the prepared resin and to study the porous structure, methods such as FTIR spectroscopy, TG, DTG, XRD, and SEM were employed. FTIR spectrums for samples prepared at different stages are presented in Figure 3. As it is seen, the peak of OH group in β -CD-modified resin, when comparing with the same peak in Ac-modified sample, is more intensive. The surface area of this peak in relation to the surface area of the aromatic CH peak in β -CD-modified resin is two times greater than that of Ac-modified sample, which is a reason for the presence of β -CD in the structure of prepared resin. To obtain more information, TG and DTG tests were conducted. As it can be seen in Figure 4 and Table II, β -CD increases the thermal stability of the resin. Also, it increases the percentage of crosslinking in the resin.

But for more precise study, the DTG of pure β -CD is presented in Figure 5. Comparing the DTG curves of resins prepared at different stages shows that DTG peak of sample modified by β -CD is sharp while DTG peak in the case of resin modified by Ac is wide. Considering the sharpness of DTG for pure β -CD, it can be concluded that β -CD presence

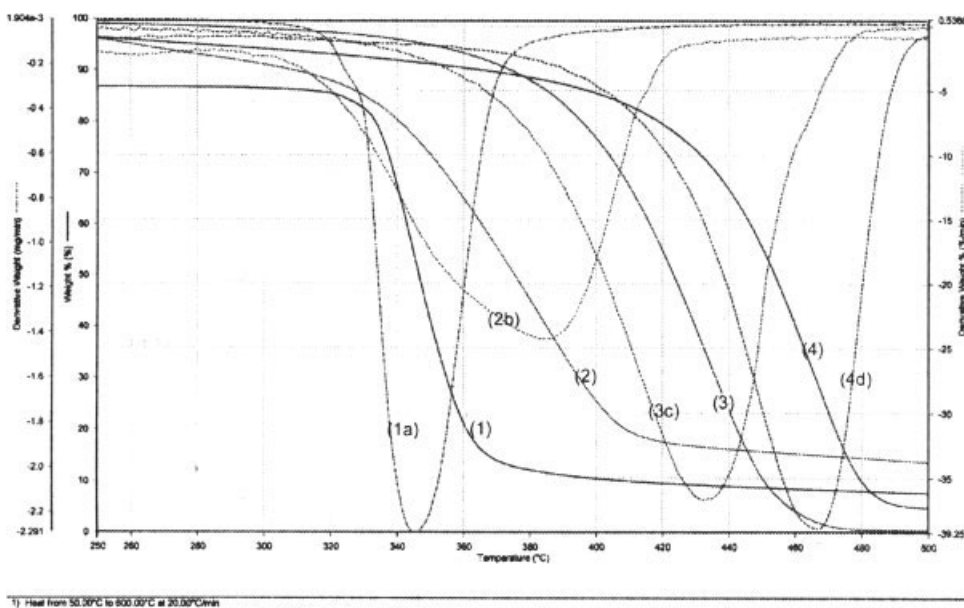


Figure 5 TG (1) and DTG (1a) thermograms of β -CD, TG (2) and DTG (2b) thermograms of PS/16%DVB, TG (3) and DTG (3c) thermograms of PS/16%DVB/Ac, TG (4) and DTG (4d) thermograms of PS/16%DVB/ β -CD.

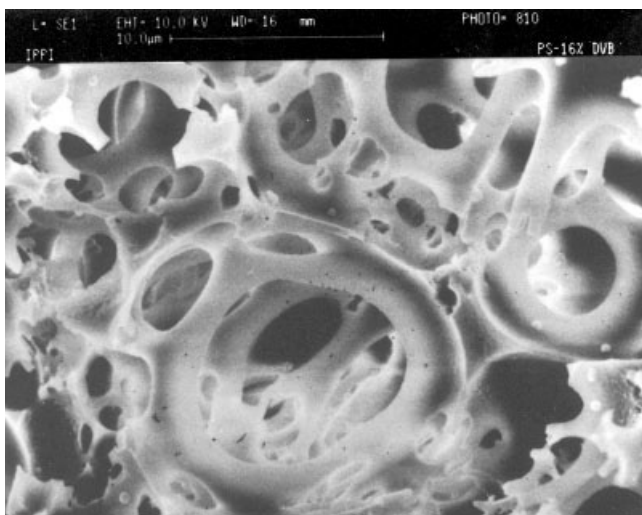


Figure 6 SEM micrograph of PS/16%DVB at ×1000 magnification.

increases the thermal stability and sharpness of the DTG for resin.

To study the porous structure of synthesized resins before and after modification with β-CD, SEM was used. SEM pictures (Figs. 6–8) indicate that:

1. Synthesized resin has porous structure completely, the pores are interconnected, and pore size is less than 10 μm.
2. Large pores (cavities) show the place of disperse phase particles (water) which are vaporized during drying after polymerization of continuous phase (St and DVB). Existing of small pores on the wall of cavities is due to the water vapor pressure in the drying process.
3. The porous structure of resin is preserved after chemical modification with Ac and β-CD.

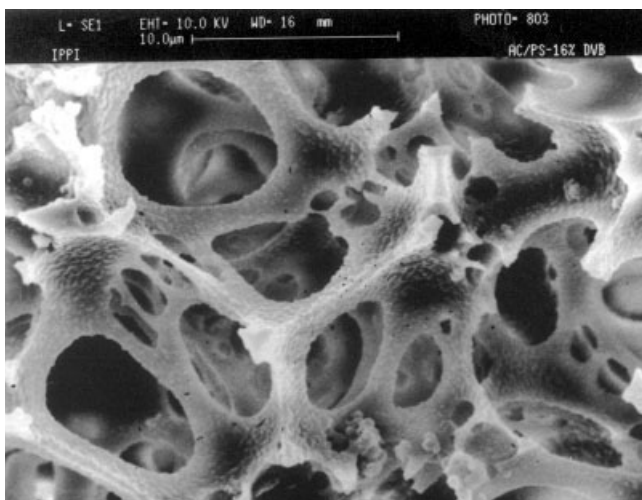


Figure 7 SEM micrograph of PS/16% DVB/Ac at ×1000 magnification.

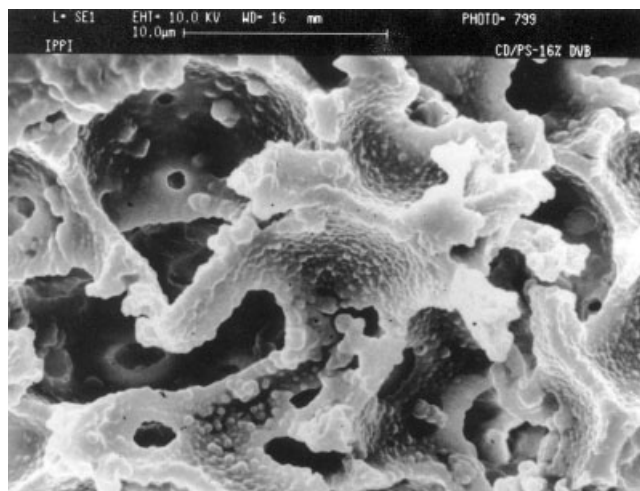


Figure 8 SEM micrograph of PS/16%DVB/β-CD at ×1000 magnification.

4. Modification of the resin with β-CD generates irregular (rough) pores which present presence of the β-CD in the resin.

One of the confident methods to find out the presence of a chemical in a compound is XRD. In this method, crystal compounds give sharp peaks at various angles; however, this is not the case in amorphous compounds. As it is observed in XRD of pure β-CD (Fig. 9), presence of sharp peaks indicates the crystal structure of β-CD. β-CD exhibited characteristic peaks at 9.1, 10.8, 12.5, 14.6, 15.4, 17.0, 17.7, 18.8, 19.0, 19.5, 20.9, 21.4, and 22.8° because of its crystal-line nature.¹³

Powder XRD pattern for samples prepared at different stages can be seen in Figures 10–14. For primary samples like PS/16%DVB and PS/16%DVB/Ac, there are no sharp peaks that are characteristic of crystal region of β-CD; however, sharp peaks appear for PS/16%DVB/β-CD. These peaks can be observed in some angles, which shows the presence of β-CD in the final sample. According to the method proposed and applied by Hendus and Schnell,¹⁴ the ratio of the passing intensity of X-ray through crystal regions to the total passing intensity was determined for calculation the percentage of crystallinity using the following equation:

$$\% \text{ crystallinity} = I_c \times 100 / (I_c + I_a)$$

where I_c is passing intensity through crystal region and I_a is passing intensity through amorphous region.

Therefore, a line was drawn from intensity point at $2\theta = 1.7^\circ$ tangent to minimum of the curve. By continuing this line, it will cross the curve at the other side. The surface area between the line and the curve is considered as I_c for crystal regions. Using I_c and total surface

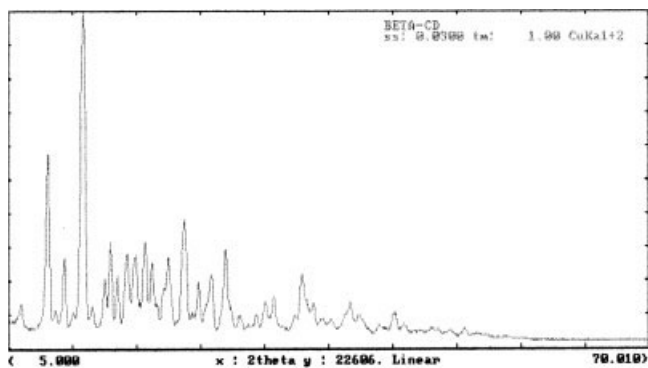


Figure 9 Powder XRD pattern for β -CD.

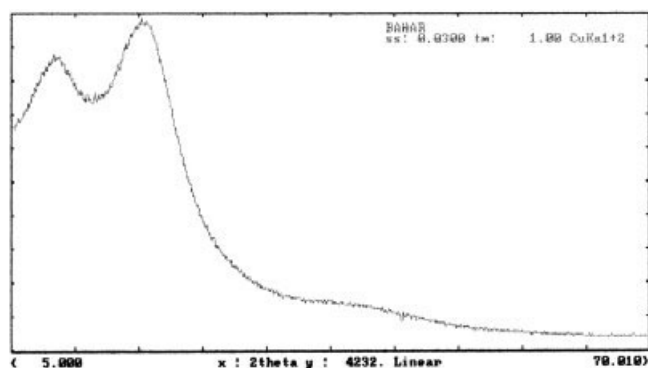


Figure 12 Powder XRD pattern for PS/16%DVB/ β -CD.

area under the curve or $I_c + I_a$ in the formula, the percentage of crystallinity can be calculated.

By calculating above quantity for three samples, i.e., PS/16%DVB, PS/16%DVB/Ac, and PS/16%DVB/ β -CD (Table III), it is seen that the percentage of crystallinity for sample PS/16%DVB/ β -CD has the highest value that indicates the presence of β -CD in prepared sample.

CONCLUSIONS

In this article, the concentrated emulsion was prepared by dropwise addition of double-distilled water to a

solution containing St, DVB, emulsifier, and initiators. Then the continuous phase of prepared emulsion (i.e., monomer) was polymerized to generate PS-DVB resin. The PS-DVB resin was chemically modified with β -CD.

Results of FTIR, DSC-TG, SEM, and XRD analyses, used to evaluate the produced resins, can be summarized as follows:

Concentrated inverse emulsion polymerization was used for making chromatography columns (based on crosslinked PS-DVB) with pore sizes less than 10 μm .

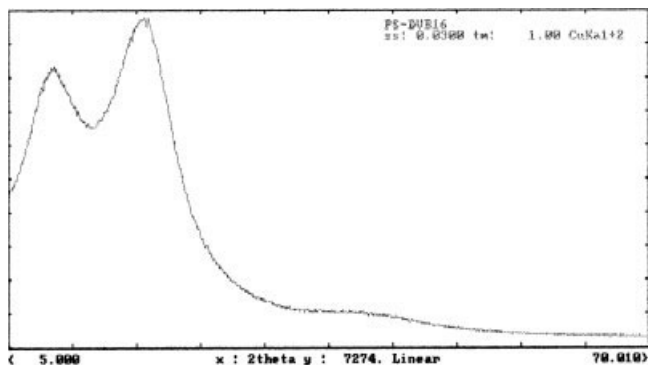


Figure 10 Powder XRD pattern for PS/16%DVB.

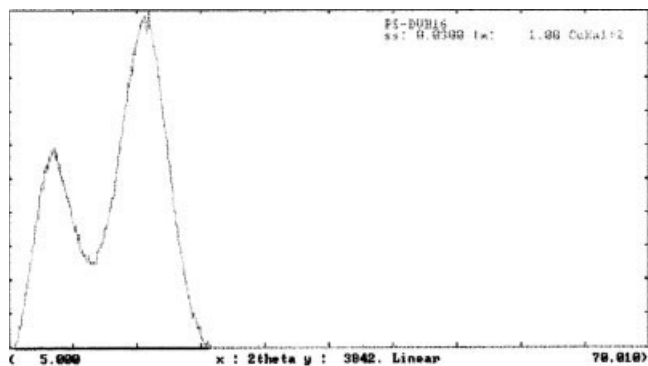


Figure 13 Normalized powder XRD pattern for PS/16%DVB.

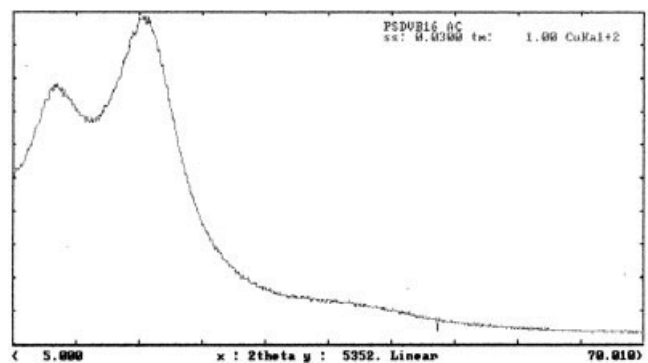


Figure 11 Powder XRD pattern for PS/16%DVB/Ac.

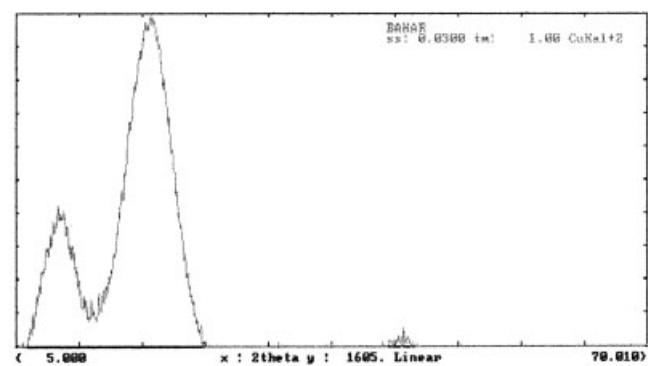


Figure 14 Normalized powder XRD pattern for PS/16%DVB/ β -CD.

TABLE III
Calculated Crystallinity Percent

Sample	Crystallinity (%)
PS-16%DVB	48
PS-16%DVB/Ac	54
PS-16%DVB/ β -CD	76

According to DSC-thermal gravimetry thermograms, it was confirmed that the residual monomer concentration after polymerization process is negligible.

For application of these columns in chiral chromatography, the β -CD is chemically fixed on the PS-DVB resin surface.

The presence of hydroxyl groups in the PS-DVB resin after chemical modification were confirmed by FTIR spectroscopy.

According to TG-DTG, by chemical modification of the PS-DVB resin with β -CD, thermal stability increased up to 446°C.

The structure of columns was analyzed by SEM. SEM evaluations showed that the porous structure of PS-DVB resin was maintained intact after the chemical modification with β -CD.

According to X-ray data, the presence of crystalline domain that is related to β -CD is confirmed.

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