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HIGHLY PERMEABLE OPEN-PORE POLYURETHANE COLUMNS FOR LIQUID CHROMATOGRAPHY

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SUMMARY

Novel highly permeable polyurethane chromatographic columns have been prepared by the *in situ* polymerization of toluene–carbon tetrachloride solutions of a polyol and an isocyanate which have been drawn into narrow-bore glass tubing. The agglomerated spherical polyurethane particles are bonded to each other in a rigid monolithic structure and are very homogeneous; depending on polymerization conditions, particles 1 to 10 μm in diameter can be prepared. Even though the columns are filled with very small particles, they show extremely high permeabilities. For example, 1-m × 2.3-mm-I.D. columns exhibit less than 100 p.s.i. inlet pressure at a 1.0 ml/min flow-rate with most solvents. Owing to the high capacity of the polyurethane columns, high-speed analytical separations have been performed at <3 p.s.i. inlet pressure and preparative-scale separations have been performed on milligram quantities in less than 1 h.

INTRODUCTION

Among the many synthetic polymers which have been used as chromatographic column packings, open-pore polyurethane (OPP) is one of the most unique in that polymerization occurs *in situ* and results in a highly permeable support of spherical particles. First used in a column by Ross and Jefferson[1] and subsequently described by Salyer et al.[2], OPP has been demonstrated to be a versatile, efficient gas chromatographic (GC) support[3]. Lynn et al.[4] demonstrated OPP columns can be prepared with a number of formulations and used in liquid chromatography (LC) with reasonable efficiency. Ross[5] has recently reviewed all of the OPP column development in GC and LC to date.

This investigation involves basic studies on OPP in LC systems with respect to particle size and size distribution, gross packing structure, column permeability and the effects of particle swelling by polar solvents, the type of solute–packing interaction (*e.g.*, liquid–solid, liquid–liquid) of various OPP formulations, and the capacity of different OPP formulations. A solvent compatibility study has been performed and several rapid analytical separations have been demonstrated.

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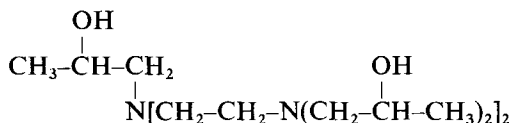
EXPERIMENTAL

Apparatus

LC was performed using a reciprocating piston pump (Chromatec, Model 3000-1), a 254/280 nm UV flow cell detector (Chromatronix, Model 220), and a 10-mV strip chart recorder (Linear Instruments, Model 251). Microbore columns were prepared by cutting thick-walled soft glass tubing (6.5 mm O.D., 2.3 mm I.D.) to the desired length followed by cutting grooves in the glass 1.5 mm deep, 5.5 mm from each end of the tube to facilitate the use of Chromatronix tube end fittings. PTFE column end fittings (G-nut, split ring, disc, G-bushing, and tube end fittings; Chromatronix) were used on the glass columns, providing connectors that were leak proof up to 500 p.s.i. Sample injection was made using an on-column septum injector (Chromatronix, Model 183 A8) and a 10-μl syringe (Hamilton). PTFE tubing (0.063 in. O.D. $\times$ 0.023 in. I.D.) and tube end fittings (Chromatronix) were used to connect the liquid streams of the system and a 10-ft. length of PTFE tubing (0.063 in. O.D. $\times$ 0.012 in. I.D.) was attached to the outlet of the detector as a restrictor tube to pressurize the flow cell and prevent bubble formation. Some preparative-scale chromatography was performed using a 58-cm $\times$ 6.3-mm-I.D. glass column (Chromatronix, Model LC-6M-23) and the appropriate fittings.

The permeability of an OPP column with a series of solvents was calculated from viscosity and density measurements of the solvents and measurements of flowrate through the column. Viscosities of the solvents were measured at 24.9° using a Cannon–Ubbelohde semi-micro viscometer (Wescon Instruments, Santa Clara, Calif., Model 229-102, 0.8 to 4 range) and an automatic viscosity timer (Wescon Instruments, Model 220). Densities of the solvents were measured at 24.9° with a 10-cc pycnometer. Flow-rates of the solvents through an OPP column at a constant pressure were measured using at the inlet of the column a 10-ft. coil of 1/4-in. copper tubing which contained the solvent and was submerged in a constant-temperature bath (Messgerate-Werk Lauda) at 24.9° connected to a two-stage regulator on a nitrogen tank.
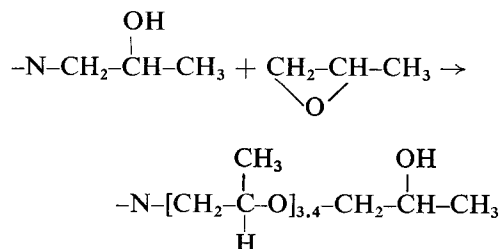
Scanning electron micrographs of the OPP were taken using a Cambridge Stereoscan Mark II. The polyurethane samples were coated with a 100- to 200-Å layer of Al by thermal evaporation *in vacuo*.

Materials

OPP is formed when a solution containing 0.1 to 0.3 g/cm^3 of a polyaryl-polyalkylene-polyisocyanate and a polyol react to form the insoluble polymer. The polyisocyanate used in this study was Mobay Chemical Company Mondur MR, which is a mixture of *p,p'*-diphenylmethylene diisocyanate and lesser amounts of the tri-, tetra-, and pentaisocyanates having an average functionality of ~2.7 NCO groups and an equivalent weight of 132. The polyol used to prepare the OPP was Union Carbide LA-475, which is a mixture of pentahydroxy compounds obtained from the oxypropylation of diethylenetriamine. The oxypropylation of the amine hydrogens results in an intermediate stage in this pentahydroxy compound,

$$\begin{array}{c}
\mathrm{OH} \\
| \\
\mathrm{CH_3-CH-CH_2} \qquad\qquad \mathrm{OH} \\
\qquad | \qquad\qquad\qquad\qquad\qquad | \\
\qquad \mathrm{N[CH_2-CH_2-N(CH_2-CH-CH_3)_2]_2}
\end{array}$$

and oxypropylation continues at the hydroxyl hydrogens until the average equivalent weight of the mixture has reached 118,

$$
\text{--N--CH}_2\text{--}\overset{\overset{\displaystyle OH}{|}}{\text{CH}}\text{--CH}_3 + \underset{\diagdown O \diagup}{\text{CH}_2\text{--CH--CH}_3} \rightarrow
$$

$$
\text{--N--[CH}_2\text{--}\underset{\underset{\displaystyle H}{|}}{\overset{\overset{\displaystyle CH_3}{|}}{\text{C}}}\text{--O]}_{3,4}\text{--CH}_2\text{--}\overset{\overset{\displaystyle OH}{|}}{\text{CH}}\text{--CH}_3
$$

with the functionality of 5 hydroxyl groups per molecule.

A toluene–carbon tetrachloride (60:40) solvent mixture was chosen as the medium for the polymerization reaction. This particular solvent mixture has a density equal to that of the polyurethane particles. The monomers are soluble, but the polymer is insoluble in this solvent mixture. Consequently, the precipitated polymer beads remain suspended as they are formed rather than setting to the bottom, and a highly permeable agglomerated bead matrix results. The solvent mixture is stored over molecular sieves to exclude water, which would otherwise react with the monomer.

Column preparation

Columns of 50-cm and 100-cm length were filled by injecting the reactant–solvent mixture into the bottom of the vertical column with a plastic syringe connected to the column by a 5-cm-long rubber tube. After filling, the rubber tube was clamped off. A similar rubber tube on the top of the column was left unclamped and used to hold a head of solvent so the polymer would not dry out during the 24- to 48-h polymerization period.

Columns of 5-cm and 10-cm length were filled by submerging the column in the reactant–solvent mixture contained in a plastic container of appropriate size. Solvent was placed over the polymer to prevent drying out during the polymerization. After polymerization, the outsides of the columns were scraped to remove the polyurethane and wiped clean with a cloth moistened with acetone.

All columns were rinsed with 100 ml *n*-heptane and 100 ml of the eluting solvent to be used before connecting the outlet to the UV detector. A non-sloping baseline was usually observed immediately following this treatment.

A number of different polyurethane formulations were used in this study. Two parameters are used to define each column and formulation. The bulk density number, as defined earlier[3], is a measure of the amount of reactants and therefore polyurethane product per unit volume of column in g/ml. An OH/NCO functionality ratio is also used to indicate the stoichiometry of the reactants. For example, let us consider the two polyurethane products of Table I. In each case the bulk density of the polyurethane product is 0.197 g/ml; however product No. 2 contains over 50% unreacted hydroxyl groups compared to product No. 1, which should contain very few unreacted hydroxyl groups because it is the result of a stoichiometric reaction. All columns are, therefore, designated with a bulk density number and an OH/NCO functionality ratio.

TABLE I

OPP FORMULATIONS

	Material No. 1	Material No. 2
LA-475, g	2.84	4.00
Mondur MR, g	3.16	2.00
Solvent, ml	25.0	25.0
Density, g/ml	0.197	0.197
OH/NCO	1.00	2.22

RESULTS AND DISCUSSION

OPP consists of agglomerated spherical particles that are bonded to each other in a rigid monolithic structure as shown in Fig. 1. Depending on polymerization conditions, particles 1 to 10 μm in diameter can be prepared and, as the 1020 $\times$ micrograph demonstrates, the particles have a very narrow size range. The 5100 $\times$ micrograph demonstrates the spherical shape of the particles. The convolutions on the surface of the particles shown in these photomicrographs can only be seen with high-resolution electron microscopes, and, therefore, have not been reported until now. Although the rough surface character is not believed to be an artifact of the coating process necessary to prevent charge build-up, heating from the electron beam could be contributing to it to some extent.

The narrow particle-size range and spherical shape are important in keeping column permeability high when the particles are so small. The permeability is also dependent on the bulk density of the polyurethane. Hileman et al.[3] found that a bulk density of 0.154 g/ml was the most efficient for GC columns and Lynn et al.[4] have performed LC studies with 0.180 g/ml bulk density columns. For LC columns with small particle diameter ($<$10 μm), mobile phase peak broadening predominates over the other peak broadening contributions[6] and, therefore, higher-density polyurethane formulations result in more efficient columns. The columns used in the present study had a bulk density of 0.197 g/ml.

For practical LC one would prefer to operate with highly permeable columns because expensive pumping systems are not necessary and separations can be performed with low-cost low-pressure equipment. Fig. 2 shows the volume flow-rate of a solvent series through a 50-cm $\times$ 2.3-mm-I.D. column at 50-p.s.i. inlet pressure. The solvent is changing from 100% n-heptane to 100% 1,2-dichloroethane and the OPP formulation was 0.197 g/ml density and OH/NCO = 2.22. With n-heptane there is an appreciable flow-rate (over 2.5 ml/min) yet with 1,2-dichloroethane the flow-rate drops off drastically to less than 0.2 ml/min.

An obvious reason for this large change in flow-rate is the increasing viscosity of the solvent, which is also shown in Fig. 2. To normalize the data for solvent viscosity the specific permeability, K^0, is calculated for each solvent mixture. The specific permeabilities are shown in Fig. 3 for the various solvents. This significant reduction in the specific permeability on going from n-heptane to 1,2-dichloroethane demonstrates the loss in openness of the OPP as the polyurethane is swollen by the more polar solvent.

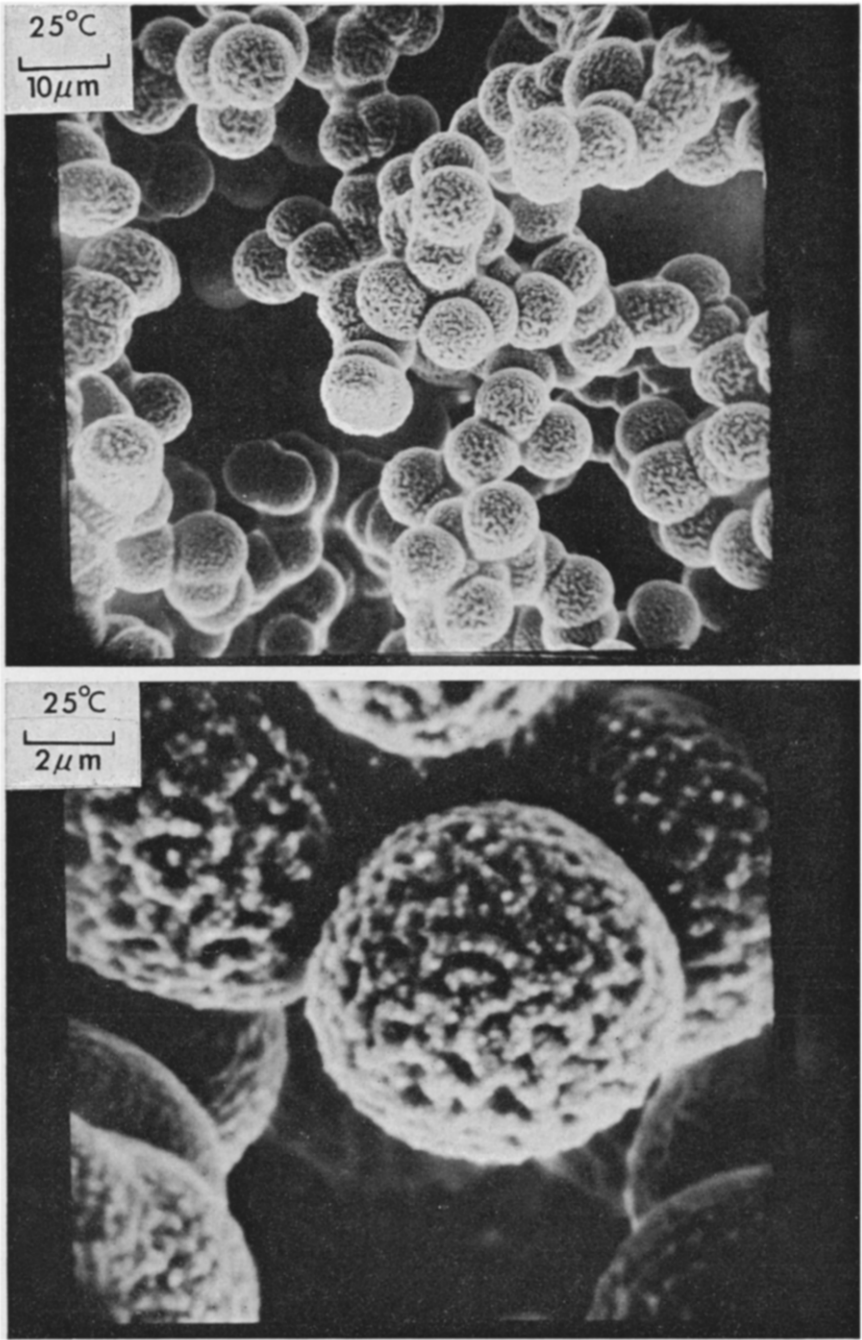It is probably necessary to swell the polyurethane to some extent for it to

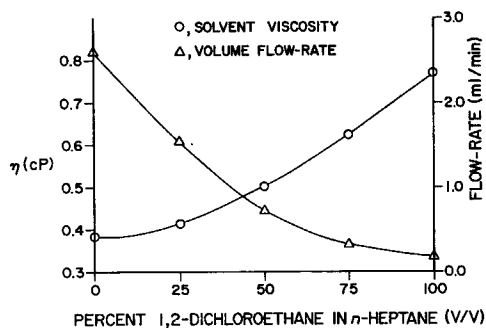Fig. 1. Scanning electron micrographs of open-pore polyurethane (above, 1020 × ; below, 5100 ×).

Fig. 2. Volume flow-rate through a 50-cm × 2.3-mm I.D. OPP column (0.197) at 50 p.s.i. and solvent viscosity *versus* solvent composition.
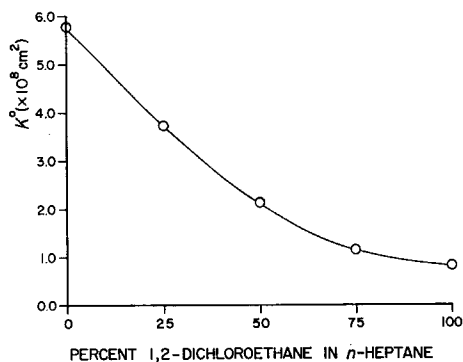

Fig. 3. Specific permeability of an OPP column (0.197) *versus* solvent composition.

TABLE II

SPECIFIC PERMEABILITY OF LC COLUMNS

Column type	Particle range (μm)	Average particle size (μm)	K^0 (cm² × 10⁸)	K^0/d_p^2
CSP beads				
(2.1 mm I.D.) (ref. 7)	<37	30	2.2	0.0024
Diatomaceous				
earth (ref. 7)	5–15	10	0.20	0.0020
Silica gel (ref. 7)	5–10	7.5	0.092	0.0016
Porous silica				
microspheres (ref. 7)	5–6	5.5	0.077	0.0025
OPP				
(OH/NCO = 2.22)				
(0.197 g/ml)				
with *n*-heptane	3–5	4	5.8	0.36
with 1,2-dichloroethane	4–6	5	0.82	0.033

exhibit appreciable separating ability in LC. With *n*-heptane as eluting solvent, no solute tested, whether polar or non-polar, was appreciably retained on an OPP column; however, when only small amounts (10%) of a polar solvent are added to the *n*-heptane, polar solutes are retained to some extent. In effect, in *n*-heptane the unswollen OPP appears to act as a zero-capacity support in LC even though in GC significant retentive characteristics have been observed[3] and separations performed on uncoated OPP.

The specific permeability of OPP is compared to other LC supports in Table II. Examination of the dimensionless quantity K^0/d_p^2 permits comparison of the specific permeabilities for the various diameter supports on a common basis[7]. The OPP packing is between one and two orders of magnitude more permeable (depending on solvent polarity) than any of the other supports.
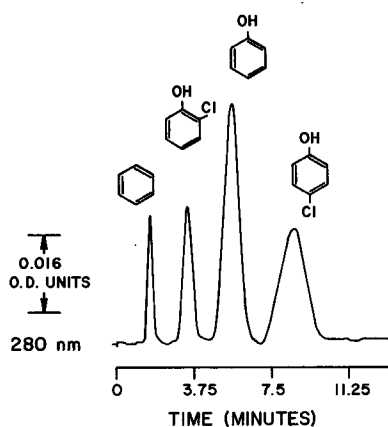

Fig. 4. Separation of phenol and derivatives on a 50-cm OPP column (0.197 g/ml bulk density; OH/NCO = 2.22; 1,2-dichloroethane solvent; 1.0 ml/min flow-rate; 300 p.s.i.).

Fig. 4 shows the separation of four solutes on a 50-cm × 2.3-mm-I.D. OPP column with 0.197 g/ml bulk density and OH/NCO = 2.22. Owing to the high capacity exhibited by certain OPP formulations, as will be discussed below, this same separation can be accomplished on a 5-cm-long × 2.3-mm-I.D. column, as demonstrated in Fig. 5. The separation of these four solutes in 4 min at less than 3 p.s.i. inlet pressure can be considered high-speed low-pressure LC and it is possible because of the high permeability exhibited by the unique OPP packing. The phenol peak has a k' (capacity factor) value of 3.4 and over 175 plates are generated by the 5-cm-long column. This is equivalent to over 3,500 plates/m.

The separation on the 5-cm column also demonstrates an empirical guideline which might be applied to analytical LC: that column length should usually be increased only to increase column capacity. If a column of given length has sufficient capacity for a solute mixture, the resolution can be increased more effectively by lowering the flow-rate than by increasing the column length at the same flow-rate. The dual advantage in using the shortest possible column containing the needed capacity is that in addition to the efficiency increase, the inlet pressure drops off drastically
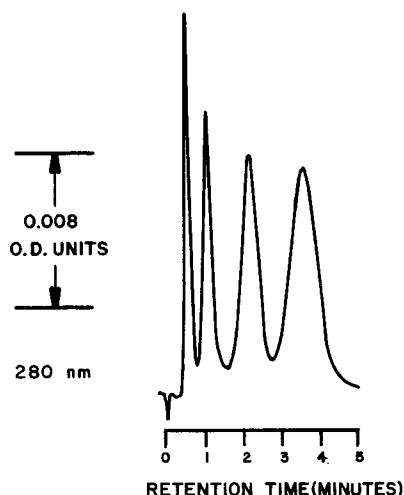
Fig. 5. Separation of phenol and derivatives on a 5-cm OPP column. Elution order: benzene, *o*-chlorophenol, phenol, *p*-chlorophenol (0.197 g/ml bulk density; OH/NCO = 2.22; *n*-heptane–1,2-dichloroethane (50:50) solvent; 0.4 ml/min flow-rate; <3 p.s.i.).

because the short columns require only the low flow-rates for elution in a reasonably short time[8].

OPP formulations having polyol in excess of 1:1 functional group stoichiometry exhibit high capacities relative to OH/NCO = 1.0 formulations. Fig. 6 shows the elution of phenol on three different OPP columns. The solid line elution curve was obtained on a column with OH/NCO = 2.22. On this column the symmetrical peak did not broaden and the retention time did not change even with the largest sample injected, 0.3 mg of phenol. Apparently the excess polyol acts effectively as a bonded
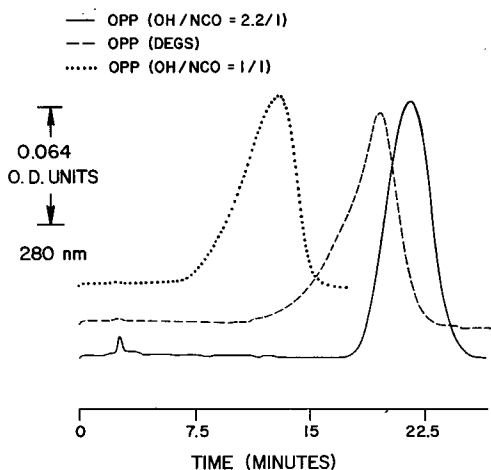

Fig. 6. Elution curves of phenol on three OPP formulations. (50 cm × 2.3 mm I.D. columns; *n*-heptane–1,2-dichloroethane (50:50) solvent; 0.9 ml/min flow-rate; 3 μg phenol sample; 0.197 g/ml bulk density.)

stationary phase. The chromatogram with an OH/NCO = 1.0 formulation (dotted line) showed leading peaks for samples from 1 μg up to 0.3 mg with shorter retention times. This peak shape, characteristic of the anti-Langmuir isotherm, indicates gross overloading of the column to the extent that the solute is acting as its own stationary phase. Even with a low-capacity formulation, the separation shown in Figs. 4 and 5 can be performed if the total sample was only 0.05 μg. With larger samples the capacity of the column was exceeded if an OH/NCO = 1.0 formulation was used. The dashed line elution curve is from an OPP column coated with diethyleneglycol succinate (DEGS). A column was prepared with an excess of NCO (OH/NCO = 0.79) followed by slowly flushing the column with DEGS-saturated chloroform for 8 h. Complete reaction of the active hydrogen of DEGS would correspond to a column containing ~10% DEGS. From the figure, phenol is definitely retained longer than on the low-capacity OPP, yet peak shape indicates overloading again.

By utilization of the high capacity of the OH/NCO = 2.22 formulation, pre-parative-scale separations of the chlorophenol isomers have been performed on a 58-cm × 6.3-mm-I.D. column. Fifty milligrams of total sample separated and eluted in 1 h at a flow-rate of 1.25 ml/min at ~100 p.s.i. A n-heptane–1,2-dichloroethane (50:50) solvent was used.

LC column packings must be able to withstand the effects of exposure to a wide range of polar and non-polar solvents. The results of an OPP–solvent compatibility study are presented in Tables III and IV, where the OH/NCO formulations were 2.22 and 1.0, respectively. The solvents evaluated are listed in increasing order of polarity as defined by δ, the Hildebrand solubility parameter[9]. The percent weight loss of OPP after passing 1 liter of solvent through a 10-cm column is shown in the right-hand column of each table. For the OH/NCO = 2.22 formulation, in general, the poly-urethane weight loss increases with solvent polarity. Apparently, as the OPP swells it loses unreacted polyol or possibly some low-molecular-weight soluble oligomers are removed from the polyurethane. Table III shows the cumulative weight loss for 1.5

TABLE III

OPP–SOLVENT COMPATIBILITY

0.197 g/ml bulk density, OH/NCO = 2.22.

Solvent	Solvent polarity (δ)*	Weight % OPP loss (1 liter)
n-Heptane	7.4	0.2
Cyclohexane	8.2	0.8
Hexanes	—	2.2
Ethyl acetate	8.6	6.9
Toluene	8.9	9.4
Chloroform	9.1	9.9
Tetrahydrofuran	9.1	9.5
1,2-Dichloroethane	9.7	8.9
		10.2 (1.5 l)
		10.7 (2.0 l)
Isopropanol	10.2	8.8

* δ = Hildebrand solubility parameter.

TABLE IV

OPP–SOLVENT COMPATIBILITY

0.197 g/ml bulk density; OH/NCO = 1.0.

Solvent	Solvent polarity (δ)*	Weight % OPP loss (1 liter)
Tetrahydrofuran	9.1	1.7
Dichloromethane	9.6	1.5
Isopropanol	10.2	1.0

* δ = Hildebrand solubility parameter.

and 2.0 l of 1,2-dichloroethane and it is seen that the weight loss per milliliter drops off sharply, indicating no gross dissolution or destruction of OPP is occurring. (For a 10% weight loss on a calculated density of 0.197 g/ml column with initial OH/NCO = 2.22, assuming the loss is all polyol, the column actually is 0.181 g/ml in bulk density with OH/NCO = 2.01.) The conclusion that no gross dissolution or destruction is occurring is supported by the results in Table IV. In the OH/NCO = 1.0 formulation no excess polyol or low-molecular-weight oligomers are present and even in polar solvents the percent weight loss never exceeds 1.7%.

Two additional separations are shown in Figs. 7 and 8, demonstrating the utility of the OPP, especially when the excess polyol acts as a stationary phase resulting in a high-capacity support. Fig. 8 is the separation of benzene and nitrobenzene in 4 min at only 50 p.s.i. using ethanol as the polar constituent of the solvent.
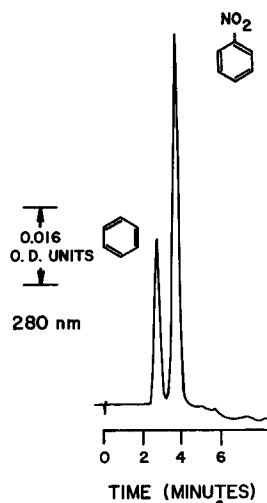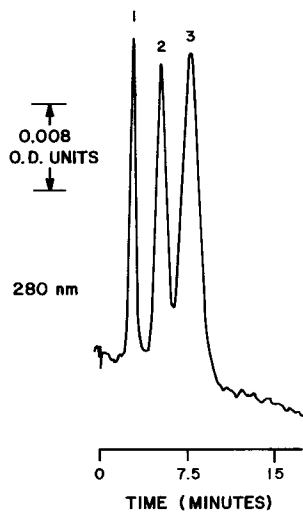

Fig. 7. Separation of (1) benzyl alcohol,.(2) cinnamyl alcohol, and (3) o-chlorophenol on OPP. (0.197 g/ml bulk density; OH/NCO = 2.22; 50-cm × 2.3-mm-I.D. column; n-heptane–1,2-dichloroethane (50:50) solvent; 0.85 ml/min flow-rate; 60 p.s.i.)

Fig. 8. Separation of benzene and nitrobenzene on OPP. (0.197 g/ml bulk density; OH/NCO = 2.22; 50-cm × 2.3-mm-I.D. column; n-heptane–ethanol (70:30) solvent; 0.7 ml/min flow-rate; 50 p.s.i.)

CONCLUSIONS

OPP offers a number of advantages as an LC packing due to its unique structure and method of column preparation. The spherical particle shape, narrow particle size distribution, and the openness of the gross packing structure are responsible for the extremely high permeability exhibited by OPP. The small particle size allows efficient separations to be made, resulting in a packing which allows one to perform inexpensive high-speed low-pressure liquid chromatography. In addition, column preparation consists of simply filling the column with a liquid rather than time-consuming, tedious settling or forced slurry techniques used for small-diameter particles. Also, OPP is compatible with many popular LC solvents of all polarities.

Owing to the high capacity of certain OPP column formulations, analytical separations can be performed at very low pressures and preparative separations of up to 50-mg quantities of solute have been accomplished in 1 h. The potential exists to carry out gram-level separations on larger-diameter columns.

Column formulations containing an excess of polyol have demonstrated that the polyol is a useful permanently bonded stationary phase in the OPP matrix. Any liquid phase or functional group can be permanently bonded to the OPP if the molecule contains an active hydrogen which can react with the NCO, such as in the DEGS-coated column.

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