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Polymer supports with high accessibility

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Abstract - The parameters governing the accessibility of functional groups in catalysts or organic reagents supported on polymer resins are discussed. They include the microenvironment contribution of the polymer chain, the viscosity and crosslink density inside the gel or microgel particles, as well as thermodynamic compatibility of the reaction medium with the polymer structure. They also include the texture of a porous resin which is fully described by the synthesis process that may be used, as well as the methods already used to obtain the pore size distribution in the swollen state. Some recent directions worked out in order to improve the accessibility are described and all the discussions are illustrated by a few selected examples.

INTRODUCTION

Research on polymer-supported reagents and catalysts is motivated by two major advantages. The first and main one is the physical separation of the supported reagent from the substrates and products. Consequently, it is possible to use a large excess of one of the reagents so that the reaction can be almost drawn to completion for the anchored reagent, and such a possibility is very useful in sequential reaction such as the so-called Merrifield synthesis of oligopeptides (ref. 1). Physical separation also allows an easy recycling of expensive catalysts (such as noble metals (ref. 2)), or of toxic products (such as hexamethylphosphortriamide (ref. 3)), or also the use of corrosive acid catalysts (ref. 4). The second expected kind of advantage is the "polymer effect" which may enhance activity of the catalyst by site isolation or, on the contrary, by cooperative effects of neighbouring groups.

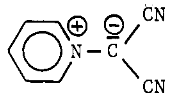
However, industrial applications are not frequent except for the Merrifiled synthesis and the acid catalysts. This is due to a few major drawbacks. One is the stability of the supported catalysts; for that reason the hydroformylation of olefins with supported rhodium catalysts, which has been extensively studied, was not developed (ref. 5). Another one, especially valid for stoichiometric reactions, is the resin capacity which is limited, due to the skeleton of the support itself. The third and almost general drawback is the limited accessibility of the active sites. Most of them are not located on the solid surface, as it is the case in the classical heterogeneous catalysis, but they are inside a very viscous, more or less crosslinked polymer medium swollen with a solvent system. The purpose of this paper is to review the problem of limited accessibility of the active sites and discuss some possibilities to solve it or, at least, to limit this drawback.

A recent review by Albright (ref. 6) of the effect of pore size distribution on the performance of a functionalized porous polymer in chemical work leads to the following conclusions. The kinetics of a chemical reaction is controlled by the diffusion inside the microparticles up to the point where there are enough functional groups on the pore surface for a reversal of the kinetic control, which then involves diffusion inside the micropores (for instance, when the surface area increases above 800 m^2/g). The diffusion limitation inside the microparticles is mostly related to the crosslink density and to the size of the penetrant molecules: the larger the size of the penetrant molecule, the lower the acceptable crosslink density will be. For a kinetic control by the groups present on the surface, the specific surface area must be larger than 500 m^2/g, a value which, in fact, corresponds to a high crosslink density (at least 30 % DVB in the case of styrene resins).

We will first discuss the parameters governing the accessibility of functional groups inside a gel microparticle, and further the effect of the particle morphology, recalling that a macroporous resin essentially results from the agglomeration of crosslinked microparticles (ref. 7) at different levels. The discussion will be chiefly based upon the well-known styrene (S)-divinylbenzene (DVB) resins, although most of the features remain valid for resins such as those based on acrylates which are becoming more and more popular. We will also discuss some recent works carried out in order to improve the accessibility and we will finally give the results of an ion exchange study briefly illustrating the main aspects of the problem.

ACCESSIBILITY OF A FUNCTIONAL GROUP INSIDE A GEL PARTICLE

The reactivity of a functional group inside a polymer medium is partly governed by its microenvironment. Few studies give reliable data on this. A possible method is the study of the electronic spectrum of a solvatochromic reporter moiety attached to the polymer chain (ref. 3). Preferential interaction of parts of the polymer molecule with a reporter, and the shielding of interactions between solvent molecules and a reporter moiety of a polymer cause a shift and broadening of its solvatochromic band. Using a pyridinium dicyanomethylide probe



and Taft linear solvation energy relationship (ref. 9), Galin estimated the volume fraction of the probe solvation sphere accessible to the solvent, ϕ_s (ref. 10). It lies within the range 0.5-0.8 for a series of polymers and solvents, the fraction being greater by about 38 % for aprotic as compared to protic solvents. The same author also shows (ref. 11) that this volume fraction is dependent on the steric hindrance of the polymer substituents. Typical results are given in Table 1 and show a correlation with Taft steric parameters E_s.

TABLE 1. Correlation of volume fractions (ϕ_s) of the probe solvation sphere accessible to aprotic solvent with Taft steric constants of substituents for several polymers

	Poly(methyl methacrylate)	Poly(tert-butyl methacrylate)	Poly(diethyl fumarate)	Poly(1,1-diethylpropyl methacrylate)
ϕ_s	0.78	0.73	0.58	0.55
$-E_s$	1.1	2.9	1.2	6

According to Mikeš (ref. 8), the polarity of the microenvironment of poly(N-(2-hydroxypropyl)-methacrylamide) in water increases with the distance between the probe and the polymer backbone, being that of water for a spacer with six methylene groups. Above that number the increasing hydrophobic character of the spacer may lead to intramolecular interaction between the reporter and the polymer so that the apparent polarity again decreases. Other data by Mikeš et al.(ref. 12) show that a spacer of two methylene groups is sufficient to eliminate the solvatochromic effect of the polymer backbone, using a rigid pyridinium phenolate betaine as the probe.

However, it seems that this solvatochromic effect, and the related volume fraction accessible to the solvent give only a partial explanation of the effect of the spacer on the increase of the reactivity of functional groups attached to the spacer inside a polymer gel. It has been often reported that the main effect of a spacer is to carry the functional group outside the very viscous polymer medium . Such explanation is certainly not correct, except for non-permeable supports such as silica. For those supports with a moderate crosslink density, such as the gel-type resin (typically, 1-2 % DVB), the substrate must penetrate through the solvent swelling the polymer bead, before reacting. The medium inside the gel may be described as a semidiluted solution of polymer segments linking the crosslinks. Estimates of the internal viscosity were obtained by at least two different physical methods. One is based on an analysis of the shape of the ESR spectra of stable nitroxide radicals (ref. 13), which shows that the correlation time (and hence the viscosity) is almost doubled inside a resin with 2 % DVB swollen by benzene, as compared with a simple solution of the nitroxide radical in benzene. The second method is based on the relaxation processes studied by ^{13}C-NMR (ref. 14). Large reduction of the T_1 value of the methyl group of toluene (the solvent swelling the resin) was observed, which was explained by a slower rotational diffusion of the solvent inside the polymer gel. The solvent self-diffusion rate was estimated to be reduced by a factor of 50 for 2 % DVB gels. These two methods gave different results for the same gel, reflecting the high sensitivity of the polymer conformation to the load frequency. If the nitroxide radical is anchored to the polymer (through a benzyloxy link), a tenfold increase of the correlation time is observed at a comparable crosslink level (ref. 13). Such results show that the mobility of a group attached to the polymer backbone is severely limited. We may expect that the mobility of a group attached to the polymer backbone through a spacer should be intermediate. Unfortunately, there are no data on that point at the moment. Anyway, it seems that the spacer length effect is limited at a certain level above a certain length around 10 carbon atoms and may be also limited if the amount of material added during the use significantly changes the medium polarity inside the polymer phase (ref. 15). When the DVB amount increases, the internal viscosity increases more than linearly with the DVB contents. For this reason, the substrate diffusion rate inside the gel progressively decreases with increasing DVB contents. The tenfold difference between the mobilities of a molecule dissolved inside the gel and of the same molecule attached to the polymer chain remains valid at least up to 10 % DVB.

An interesting attempt was carried out by McKenzie and Sherrington (ref. 16) who specifically located active phosphine groups at the crosslink points, and compared the reactivity of such resins with a more classical resin where the phosphine groups were introduced through the use of p-styryldiphenylphosphine. For the same amount of crosslinks, between 5 and 37 %, they did not observe any significant effect, although the chosen reaction (conversion of alcohol to alkyl chloride in the presence of CCl_4) was expected to be sensitive to the interaction between phosphine groups. Then it may be concluded that the steric hindrance and mobility of the groups are not really different if located at a crosslink point or just near the polymer backbone.

A second important feature of the S-DVB resins is the inhomogeneity of the crosslink density. There are two main reasons for that. The first one is the higher reactivity of DVB as compared with that of styrene. Actually, commercial DVB is a mixture of para-DVB, meta-DVB, para- and meta-ethylvinylbenzene (EVB) with a small amount of vinyltoluene and other impurities. Gas chromatographic analysis of the consumption of these various components (ref. 17, 18) leads to the following order of reactivity (relative values in brackets)

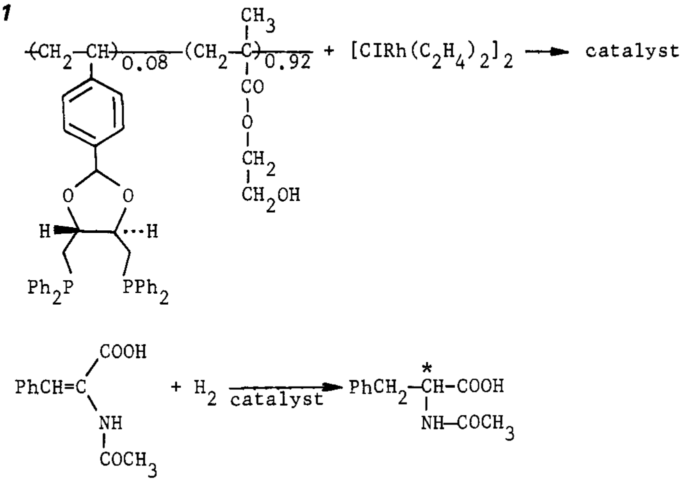
$$\text{p-DVB (7)} > \text{m-DVB (4)} > \text{m-EVB (1.4)} > \text{p-EVB} \cong \text{S (1)}$$

Then, both difunctional isomers are first reacted, p-DVB 7 times more rapidly than styrene. The crosslinking process involves the reactivity of the second DVB double bond, which is intrinsically equivalent to that of styrene (ref. 19). However, the concentration of this second double bond is the highest in the polymer produced at the beginning of the process. Then, highly crosslinked nodules tend to be formed and are dispersed in a matrix of less crosslinked material. This trend is enhanced by the thermodynamic expulsion of low-molecular-weight solvent and monomers from the crosslinked regions (ν-syneresis phenomenon). The higher viscosity inside these crosslinked nodules causes a further gel (Trommsdorff) effect, i.e. a decrease in the termination rate so that the whole polymerization rate is increased. For all these reasons, the second double bond consumption is higher than expected in the initial part of the process on the basis of the intrinsic reactivity of the double bond. The final result is an inhomogeneous distribution of the crosslinks inside the gel. One of the causes of such inhomogeneity, i.e. the higher reactivity of the crosslinking agent, may be eliminated if the two double bonds have independent reactivity, such as observed with ethylene glycol dimethacrylate. However, even in such cases the distribution of crosslinks may have some effects on the reaction kinetics, especially if one is interested to push the reaction up to completion. Thus, Morawetz and Pan (ref. 20) studied the acylation of the aniline analogue, p-aminostyrene with acetic anhydride. The aniline fluorescence is quenched after acylation, and so it is possible to follow the very end of the reaction. In homogeneous systems the plot of the logarithm of the fluorescence intensity versus time is linear through more than seven half-lives. When the aminophenyl group is introduced diluted (5 molar %) in a acrylate matrix more or less crosslinked (1 to 15 % diacrylate), a deviation from linearity is observed at about two thirds of conversion, whatever the crosslinking ratio. According to the author, this surprising result means that crosslinks may inhibit conformational transitions.

An obvious parameter for the accessibility of the reactive groups inside a polymer gel is the compatibility of the support polymer with the liquid reaction medium. The polymer gel swells more in a good solvent of the basic uncrosslinked polymer than in a non-solvent of that polymer. If the reaction medium contains two kinds of solvent, the more solvating one will be preferentially absorbed. Thus, if an organic reagent is not compatible with the polymer, it will mostly remain outside the polymer and its concentration near the supported moieties will be correspondingly low. The misunderstanding of that very fundamental fact caused a lot of disappointing results in the past. For instance, one of the first asymmetric hydrogenation systems, discovered by Kagan et al.(ref. 21) was the so called DIOP-rhodium system. In a homogeneous medium the hydrogenation of N-acetyl-α-aminocinnamic acid is carried out with up to 100 % conversion and with an 86 % optical yield. When the system was simply transposed on the Merrifield resin by anchoring DIOP to the support through the chloromethyl groups, no reaction took place. By changing the support, introducing 90 % hydrophilic comonomer units, Stille (ref. 22, 23) was also able to reach full conversion, with an optical yield similar to that of the homogeneous system (Scheme 1).

Thus, upon comparing the reactivity of homogeneous system with that of a polymer-supported reagent, it is important to measure the distribution of various reactants between internal phase of the polymer gel and the external medium. This may be easily done because a physical separation of the swollen particle and the surrounding medium is carried out by simple filtration. Another suggestion is to prepare a linear polymer of the same composition and to check its solubility in the reaction medium. If not soluble, the nature of either the solvent or of the polymer should be altered.

Scheme 1



Hydrophilic supported DIOP catalyst for asymmetric hydrogenation

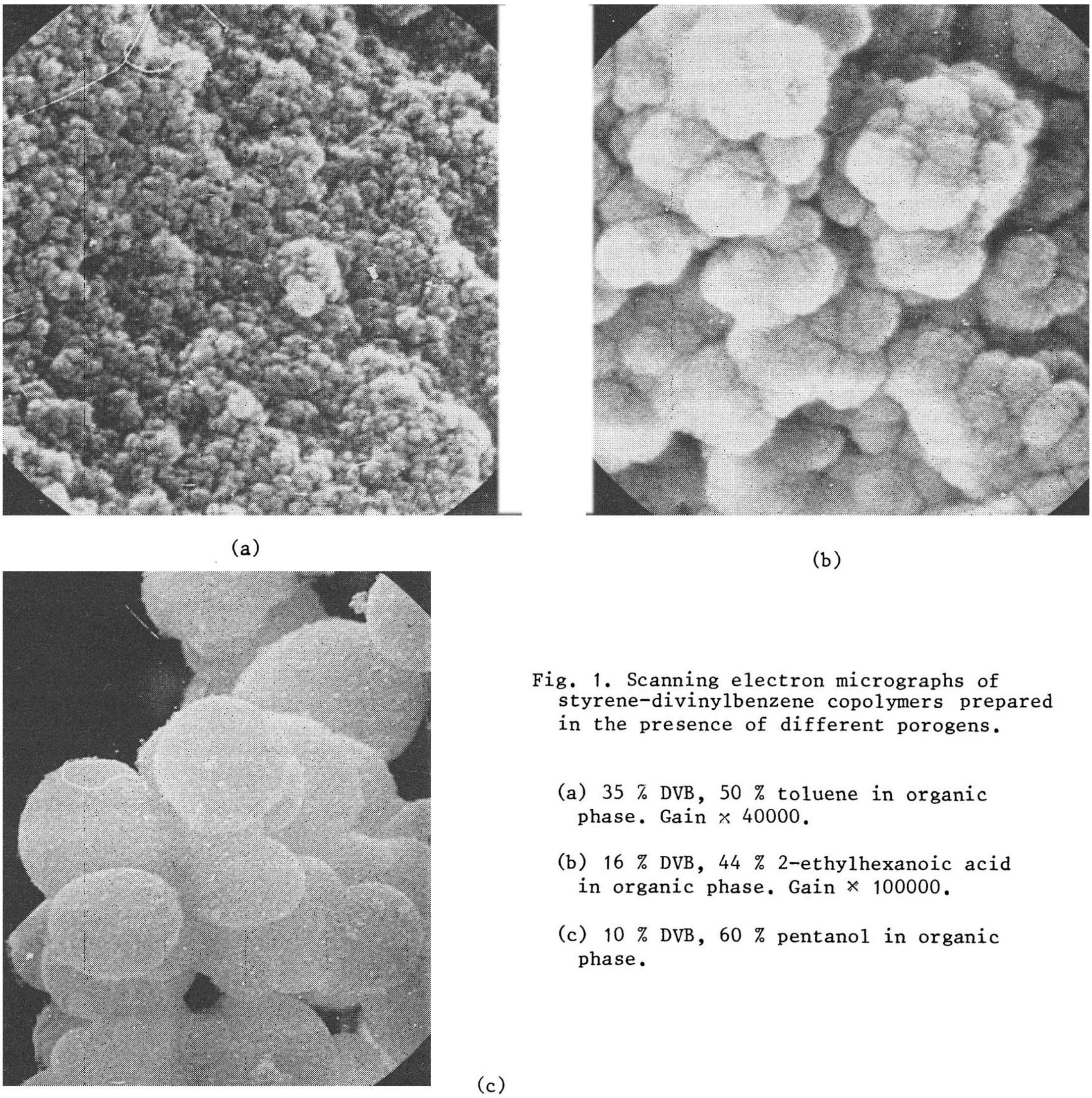
PARTICLE MORPHOLOGY

When diffusion limitations are operative, an obvious solution is to decrease the viscous material thickness to be crossed by the reactants from the surrounding medium to reach the supported reagents inside the gel, and by the products to do the reverse way. This can be done in two ways. One is to decrease the radius of the gel particles, an inverse relationship between this radius and the reaction rate indicating a diffusion limitation for this reaction. The second way is to use macroporous particles, which are actually aggregates of smaller particles. Then the reactive species rapidly diffuse through the pores and cross the smallest aggregated gel particles. In that case no conclusion can be driven from the independence of the rate on the macroporous particle size, as it is often wrongly done. The diffusion problems are namely limited to the medium inside the smallest aggregated gel particles (which are generally highly crosslinked), and possibly to the entrance of the micropores in-between these smallest particles.

Smaller gel particles can be prepared by the microsuspension process, often called emulsion because the polymer particles are prepared in the presence of surfactants using oil-soluble initiators. Improved reaction rates were initially obtained via this route by Fréchet et al. (ref. 24), and a more systematic study was carried out by Ford et al. (ref. 25-26). However, actual latexes (prepared in the presence of water-soluble initiators and with submicronic particle size) can be used, too. Efforts are presently made for obtaining the so-called core-shell latexes with an outer shell different in composition from the inner core (ref. 27), and also latexes with controlled surface functionalization. It was realized that strong acid groups present at the surface of various acrylates latexes were able to easily catalyze the hydrolysis of the ester groups of the latex itself (ref. 28). Polystyrene colloids carrying sulfonate groups on their surface were used for acid catalysis of the hydrolysis of acetates and the inversion of sucrose (ref. 29). In most cases, the rates were higher, as compared with the reaction catalyzed by conventional acids, probably due to hydrophobic interactions causing the substrate molecules to be held in the region of high acid concentration, which is the diffuse part of the electrical double layer. However, the use of such very small particles may lead to more difficult physical separation of the supported catalysts, because then ultrafilters are needed. An elegant solution of this problem should be the use of magnetized particles (ref. 30). This technique is more and more popular in the latex biomedical applications, such as the immunoassay reagents, or the removal of tumor cells by specific antigen-antibody reactions (ref. 31-34).

Macroporous resins are prepared by suspension polymerization in the presence of a diluent which may be a solvent or a non-solvent of the basic linear polymer, or also in the presence of another polymer soluble in the monomer or eventually a polymer solution.

The simplest case is when the diluent is a solvent of the basic polymer. A gel particle is obtained if the amount of the diluent is limited and if the amount of the crosslinking agent is also limited, as this is the case in the absence of solvent. When the amount of crosslinking agent is high enough, and if a good solvating diluent (solvent of polystyrene such as toluene) is used, the ν-syneresis may be strong enough so that permanent pores are created. In such conditions high surface areas (more than 500 m^2/g with a narrow distribution of very small pores, 10 nm) are obtained, together with a limited volume (around 0.3 ml/g) of large size pores. Microscopic examination of the texture of a fractured grain shows agglomerates of essentially one family of not too small nodules (20-80 nm) (Fig. 1a).


(a)

(b)

(c)

Fig. 1. Scanning electron micrographs of styrene-divinylbenzene copolymers prepared in the presence of different porogens.

(a) 35 % DVB, 50 % toluene in organic phase. Gain × 40000.

(b) 16 % DVB, 44 % 2-ethylhexanoic acid in organic phase. Gain × 100000.

(c) 10 % DVB, 60 % pentanol in organic phase.

A very similar porosity (narrow distribution of small pores and high surface area) is observed with the so-called isoporous resins (ref. 35-36). These materials are obtained upon post-crosslinking of a solution of polystyrene with bis(benzyl chloride)-containing molecules in the presence of Friedel-Crafts catalysts. Again in this case, the permanent porosity has been created under the thermodynamic forces of the ν-syneresis.

However, the materials referred to as "macroporous" or "macroreticular" resins are most often produced using a smaller amount of DVB (more than 5 % and generally around 20 %)and in the presence of large amounts of a non-solvating diluent. Then, the grain contains big agglomerates of microspheres (100-200 nm) which look as cauliflowers and show smaller nuclei (10-30 nm) more or less fused together (Fig. 1b). In between the nuclei, there is a first family of very small pores (5-15 nm) which are chiefly responsible for the high surface area of these materials. When the amount of DVB is increased, the nuclei are less fused and the area is increased. In between the microspheres, a second family of intermediate pores, meso pores is observed (20-50 nm) which may account for the moderate surface area (up to 100 m^2/g). A third family of large pores (50-1000 nm) is located between the agglomerates. This family is responsible for the high pore volumes (up to 3 ml/g) which can be measured, chiefly when the amount of diluent is higher. In a diagram with the amount of DVB on the abscissa and the amount of diluent on the ordinate, as initially proposed by Häupke and Pientka (ref. 37) a macroporous domain limited by two boundaries may be defined where this three-level morphology can be observed (Fig. 2). Under the lower boundary (low DVB and low diluent contents) a gel-type material is obtained. Above the upper boundary (high diluent content) a fused morphology is observed (Fig. 1c) where the nodules are no more visible (only the shape of the microsphere can be observed), only large pores are present and the surface area is moderate (around 20 m^2/g). However, before going to such morphology, the system did show a transient macroporous texture (ref. 17). The location of the boundaries is dependent on the nature of the diluent (ref. 38).

In these systems, phase separation occurs because the medium-solvating power for the polymer produced is decreasing upon monomer conversion. It is believed (ref. 39) that the microsphere formation results from the phase separation. Inside these microspheres, the ν-syneresis operates creating permanent microporosity and, if enough DVB is present, a high surface area is obtained. Most of the unconverted monomer remains dissolved in the dilute phase (non-solvating diluent) and upon polymerization precipitates as small particles which are captured by the existing microspheres. This phenomenon is believed to be responsible for the cauliflower aspect of the microspheres (ref. 40), although this statement may be contested because the microspheres remain swollen by preferential solvation with the monomer. Anyway, covering of the microspheres by the polymer and their fusion produced at high conversion may explain the morphology shown in Fig. 1c, above the upper boundary of Fig. 2. Both micropores and mesopores are filled up with the polymer formed in the last stages of the process and only very large pores resulting from the phase separation itself remain.

Another way to get only large pores is to use a polymer or a polymer solution in a rather good solvating medium (ref. 41). Upon polymerization the newly formed crosslinked molecules are obviously non-compatible with the porogenic polymer molecules. Crosslinked nuclei are created surrounded by a solution of a polymer which should act as a monomer reservoir to allow the growth of nuclei. In the porogenic domains, entanglement will take place, depending on the molecular weight of the polymer. Thus, the extreme sensitivity of the pore size distribution to the molecular weight of the polymer and also the dependence of pore size distribution on polymer concentration can be explained.

Although only the S-DVB system was extensively studied, it is clear that the phenomena giving rise to the various morphologies are quite general. Macroporous resins with a variety of pore size distribution can be prepared from other monomer systems by proper adaptation of experimental conditions.

Few data are available about the precise relationship between pore size or pore size distribution and the reaction rate. One of the major reasons is that the pore size distribution is usually determined on dry material, while the reactions are most often carried out in the presence of a solvent so that the support is more or less swollen. Moreover, the pore size distribution in the dry state may be widely dependent on the drying conditions. According to Galina et al. (ref. 42) this depends on the way by which the system reaches its glass transition temperature during the drying process. Hence, it should be necessary to determine the pore size distribution of the resin swollen by the reaction medium.

Very few measurements of the pore size and pore size distribution have been carried out directly on swollen resins (ref. 42-43). One method is based on small angle X-ray scattering, from which the electron density distribution in a material can be deduced. Some results published recently (ref. 44) show a pore volume fraction not very dependent on the nature of the solvent for a resin prepared using 10 % of DVB and as much octane (diluent) as the monomer. A more poweful method, the thermoporometry (ref. 45) was used in the author's laboratory (ref. 46). It is based on the measurement of the freezing point of the solvent

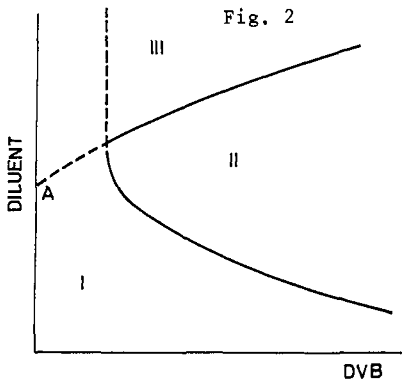
TABLE 2. Effect of the nature of resins on the performance of resin-supported rhodium-phosphine hydrogenation catalysts[a]

Resin type	Surface area m^2/g	Cl mmol/g	P mmol/g	Rh mmol/g	Turnover
Isoporous	456	205	120	17.9	0.028
Isoporous	606	245	109	6.2	0
Gel	0	144	131	14.4	0.15

[a] Rh anchored to the resin through exchange with $[RhCl(CO)_2]_2$.

TABLE 3. Influence of the catalytic activity in hexene hydrogenation on the pore texture

DVB, %	8	25	40	60
S, m^2/g	120	109	247	590
V_p, ml/g	0.53	0.71	0.75	0.75
r_p, Å	89	130	60	25.5
Cl, %	13.4	8.2	9.9	9.7
Cl, mmol/g	3.7	2.3	2.8	2.7
P, mmol/g	2.2	1.4	1.4	0.7
P/Cl	0.59	0.61	0.5	0.26
Rh, mmol/g	0.20	0.19	0.33	0.17
Rh/P	0.09	0.14	0.23	0.24
Turnover	0.27	0.32	0.09	0.16
Total activity	0.05	0.06	0.03	0.027



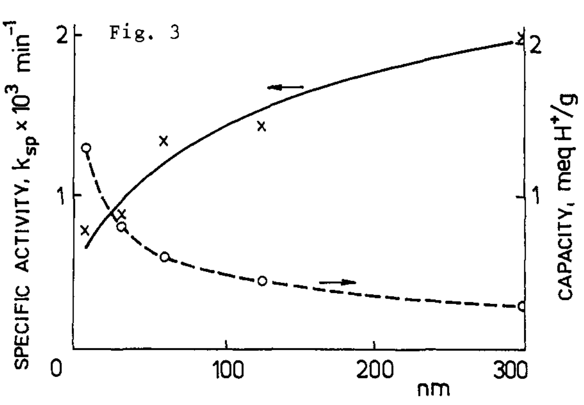


Fig. 2. Styrene-divinylbenzene copolymerization in the presence of a non-solvent diluent.
I Gel-type domain, II macroporous domain, III domain where the microspheres have been covered before the end of the polymerization, A - incipient precipitation of polystyrene in the mixture diluent-styrene.

Fig. 3. The dependence of capacity and specific activity on silica pore diameter in the hydrolysis of maltodextrins at 70°C catalyzed by silica-supported sulfonic acid. (Specific activity of H_2SO_4 and polystyrene-sulfonic acid are respectively 1.3 and 2.0×10^{-3} min^{-1}.)

inside the pores which depends on their size, being lower in smaller pores. A simple inverse relationship is valid between the pore radius r_p and freezing point depression ΔT

$$r_p = a/\Delta T - b ,$$

where a and b are constants depending on the nature of the solvent. Calorimetric measurements carried out at decreasing temperatures allow us to draw a distribution curve. To check the validity of the method, the authors made freeze-drying experiments at temperatures lower than the lower freezing points experienced, and then they used conventional methods for dry polymers (mercury intrusion). The freeze-drying method is to be recommended because it does not need a very special equipment for pore size measurement. However, solvents which are sufficiently volatile and have not too low freezing points have to be chosen.

From the author's laboratory experience and from some data reported in the literature, it seems clear that the best results in supported catalysis or organic synthesis with supported reagents are obtained using supports having essentially large pores, rather than a high surface area. Disappointing results were obtained using the isoporous resin (ref. 47). Since these resins are able to swell in both solvents and non-solvents of the backbone polymer (they swell very much in ethanol, for instance), it was expected that they lead to very accessible sites. A comparison was made with gel resins in a test involving hexene hydrogenation in the presence of a rhodium catalyst anchored on a support carrying phosphine groups. Some typical data, shown in Table 2, indicate that these isoporous resins are less efficient than the gel-type resins. Moreover, upon increasing their surface area, the activity totally disappears. Then the sizes of micropores become so small that they cannot be penetrated by the reactants. Another possible explanation is that the crosslink density of polymeric materials and the surface area are increasing in a parallel way so that the microgels become inaccessible.

When using macroporous resins (ref. 48), both the turnover number and the total activity of the same catalysts are maximum for an intermediate crosslink density and are clearly more related to the average size of the pores than to the surface area. The corresponding data are reported in Table 3.

When the surface area and crosslink density are the highest, the phosphination reaction yield is very limited as shown by the drop in the P/Cl ratio. On the other hand, the rhodium retention seems better (increasing values of the Rh/P ratio), which might indicate that these phosphine groups are more accessible. However, the turnover values are lower, which means that there are strong diffusion limitations.

Another interesting example of the influence of the pore size was the catalysis of maltose hydrolysis by porous silica functionalized with sulfonic acid groups (ref. 49). Various silicas with rather well defined pore size between 20 and 300 nm were used. The specific rate increased with the pore diameter as shown in Fig. 3. Unfortunately, the capacity, which is roughly proportional to the surface area decreases even more so that the total rate which is the product of capacity and specific rate decreases by a factor of about two and remains lower than that of gel (k_{sp} 0.8×10^{-3} min^{-1}, capacity 2.9 meq/g) or macroporous commercial styrene resins (k_{sp} 0.3×10^{-3} min^{-1}, capacity 3.7 meq/g).

TABLE 4. Selective oxidation of 2-octanol to 2-octanone with resin-supported chromic moieties

Resin	DVB %	N mole %	Functionalization technique	V_p cm^3/g	S_{BET} m^2/g	Cr % species	theory	exp.	Yield %
PVP 901	?	0.71	copolymerization	0.3	10	ion	18.7	6.3	11
						neutral	21.5	2.3	55
VP 8	?	0.71	grafting	0.2	10	ion	18.7	16.0	25
						neutral	21.5	2.5	27
FP 6	40	0.35	copolymerization	1.0	114	neutral	13.5	2.3	10
FP 8	10	0.52	copolymerization	2.4	7.7	ion	15.8	11.3	37
						neutral	17.8	13.1	80
FP 12	40	0.22	copolymerization	1.6	51	neutral	9.4	6.4	74

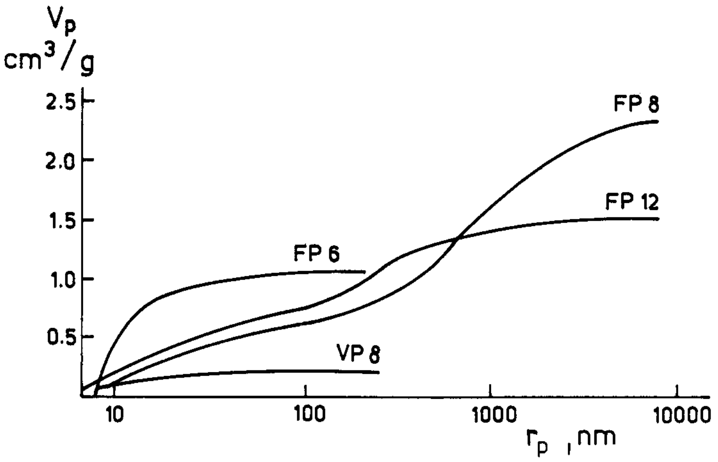


Fig. 4. Integral pore size distribution of macroporous vinylpyridine resins FP 6, FP 8 and FP 12 and a resin functionalized by grafting, VP 8.

The last example is related to the stoichiometric (as opposed to catalytic) oxidation of alcohol with hexavalent chromium moieties coordinated to supported pyridine groups (ref. 50). Both ionic chlorochromate and neutral chromium complexes were used in organic media. Chlorochromate ions are fixed from a 10 N HCl solution of CrO_3 and then the resin is washed and dried. Neutral complexes are obtained after ligand exchange from a saturated acetonitrile solution. Typical results are reported in Table 4. Both processes of chromium fixation and octanol oxidation are dependent on the nature of the support. Resin PVP 901 is a commercial one with limited porosity and low surface area; in both cases, it gives worse results. VP 8 is a commercial resin most probably prepared in the presence of solvent-type porogen, and further functionalized by grafting vinylpyridine. Series FP are macroporous resins prepared by 4-vinylpyridine copolymerization with DVB. In the case of ionic complexes, VP 8 gives the best yield of chromium fixation, but FP 8 shows the best performance in the oxidation process. On the other hand, in the case of neutral complexes, the yield of chromium fixation is quite poor except in the case of the macroporous FP 8 and FP 12, which also give the best results for oxidation. The pore size distributions of these resins are shown in Fig. 4. A comparison with the data of Table 4 points out the importance of the presence of very large pores.

SITE LOCALIZATION

The classical way to attach functional groups to a polymer is through chemical modification. A variety of functional groups may be attached through a reactive precursor group such as a chloromethyl group or lithium atom. The corresponding chemistry has been thoroughly described previously (ref. 51). The main interest in these methods is that the anchored groups are rather accessible, just because they can only be attached to accessible parts of the support. Such a functionalization is, of course, limited if the crosslink density is very high, as in the case of macroporous resins. A few data of Table 3 illustrate these features, for both initial chloromethylation and subsequent phosphination. The yield is very dependent on the swelling power of the solvent used in the functionalization process: methyl chloromethyl ether is a better solvent than heptane. The yield of the rhodium anchoring which is carried out in alcohol is always very low; however, adequate porosity and higher surface area may balance the effect of a non-swelling solvent.

The second main avenue to functionalized resins is the direct introduction of functional groups through copolymerization of the corresponding monomer. It is a very general way provided the monomer is available; a number of functional groups can be attached to styrene or acrylic monomers which are easily polymerized. The advantage of this procedure is the possibility to predict the relative location of the functional group inside the polymer chain (i.e., the sequence distribution), if the reactivity ratios of the engaged monomer are known. Another very important advantage is the possibility to introduce an active site with a preformed environment (catalyst and ligands), if the whole system may be incorporated into the same polymerizable molecule. One of the main drawbacks of the resins functionalized ab initio by copolymerization is the fact that, depending on the relative reactivity ratios, a part of the functional groups are expected to be buried inside inaccessible cores of highly crosslinked nodules. A partial solution to the problem is the delayed introduction of functional monomers. For instance, chloromethylated styrene resins were prepared by introducing vinylbenzyl chloride at various stages of the polymerization process. The accessibility of the CH_2Cl groups, judged according to the phosphination (with $P(C_6H_5)_2Li$) yield, was increased from 40 % (introduction ab initio) to up to 70 % (introduction when most divinylbenzene has been consumed after fixation of the resin morphology). The final step in this direction is the grafting of functional groups by post-polymerization, in which a charge of monomer and initiator is introduced to the preformed styrene-divinylbenzene resin. The method, first used by Schutten et al. (ref. 52), was more extensively studied in the author's laboratory (ref. 53). Good grafting yields can be obtained if the reactivity ratios of the functional monomers have values allowing efficient copolymerization with styrene; this means that the grafting takes place through copolymerization with the residual double bonds. The grafting process may be efficient with only a limited amount of residual double bond consumption. In most cases, when grafting was efficient, the consumption is limited to 20-30 %. A part of the double bonds, probably buried inside the highly crosslinked nodules, cannot be reacted at all with any reactant. Depending on the initial swelling conditions, the grafting may be limited or extensive. In all cases, accessibility of the grafted functional groups is very good, because the crosslink density in the grafted polymer chains is practically zero.

RECENT ATTEMPTS TO IMPROVE ACCESSIBILITY

Combination of a macroporous resin having essentially large pores with functionalization by post-copolymerization is expected to give the best results as far as the active site accessibility is concerned. As shown above there are two ways to get only large pores in styrene-divinylbenzene resins: the first one is to prepare these resins using a large amount of non-solvating porogen (domain III in Fig. 2), the second one is to use a macromolecular porogen or even a solution of macromolecular porogen (ref. 54). Using this latter method with polystyrene in toluene as a porogen, and further chloromethylation by post-copolymerization of vinylbenzyl chloride, ion-exchange resins were recently prepared in the author's laboratory (ref. 55). Quaternization of these resins with trimethylamine was completed at 35°C in less than 80 minutes, while 8 hours at 50°C were recommended in the case of conventional macroporous resins (ref. 56). The same intermediate resins were further transformed to methyl sulfoxide resins (ref. 57) which were much more efficient than conventional macroporous resins (with 10 or 20 % divinylbenzene) in alcohol oxidation (ref. 55).

It is worth mentioning here the so-called "pellicular resins" in which a thin layer of functionalized polymer is grafted on an inert porous or non-porous core. A first example was reported by Challa et al. (ref. 58) who grafted $Cl_3SiCH_2C_6H_4NO_2$ on non-porous silica spheres. The grafted nitrophenyl group was then reduced to amine, and after diazotation an azo initiator was obtained, capable to initiate the radical copolymerization of styrene and vinylpyridine. This copolymer was shown to be a suitable polyligand for copper ions used as enzyme-like catalysts in the oxidation of phenols. More recently, Wulff et al. (ref. 59) treated macroporous silica with trimethoxysilylpropyl methacrylate, and this material was further copolymerized with a mixture of ethylene dimethacrylate and a monomer-precursor of chiral cavities. After suitable treatment the material was used in chromatographic separations of enantiomeric substances. Although the functional layer, with an average thickness of about 10 nm, was highly crosslinked, the resistance to intraparticle diffusion was shown to be negligible. The excellent accessibility of these materials was obviously due to the choice of the starting silica having wide pores (50-100 nm).

Efficient pellicular resins were prepared in the author's laboratory using polypropylene as the core. First small spherical particles were prepared by crystallization of polypropylene solutions in a controlled manner (ref. 60). They were then peroxidized in a fluidized bed in a stream of ozonized air and the macromolecular peroxides were further used in a redox system to initiate functional monomer polymerization. Chloromethylated polystyrene was thus grafted and used as a precursor for "supported dimethyl sulfoxide" (ref. 61) or, after quaternization, as an ion exchange resin, as shown below.

CONCLUSIONS

In order to illustrate conclusively the discussion given above we describe now the results of a comparative study of an isotopic exchange experiment carried out with different resins. It was expected that there is not kinetic limitation in the ion exchange rate. Then, in a frontal chromatographic experiment, the exchange rate related to the slope of the experimental curve, is considered as determined mainly by diffusion. The anion exchange resin carrying quaternary ammonium groups is charged with ^{10}B-enriched H_3BO_3 and then a solution of natural H_3BO_3 is pumped through the column. From an analysis (isotope ^{10}B) of the eluted solution versus time, the efficiency curve is drawn, E = f(t), where

$$E = \frac{\%\ ^{10}\mathrm{B\ enrichment} - \%\ ^{10}\mathrm{B\ at\ time\ } t}{\%\ ^{10}\mathrm{B\ enrichment} - \%\ ^{10}\mathrm{B\ natural}}$$

The results are shown in Fig. 5 for four different resins.

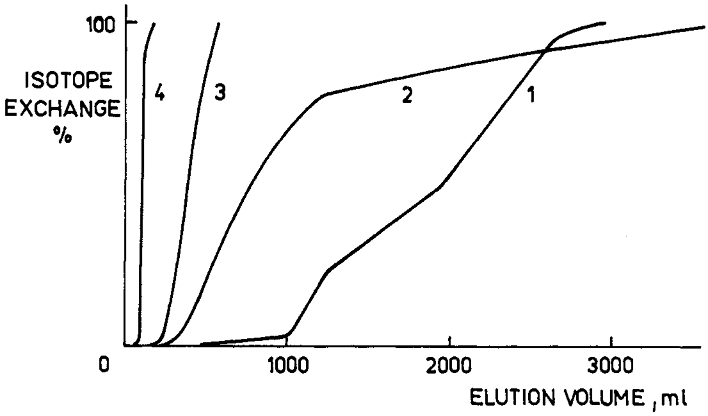


Fig. 5. Chromatographic isotope exchange of boric acid on various anion-exchange resins. (1 and 2 commercial macroporous resins, 3 experimental macroporous resin with large pores, 4 pellicular resin.)

TABLE 5. Characteristics of the resins for frontal chromatographic isotope exchange of boric acid

Resin	Diameter µm	Capacity ml	Cl$^-$ mol/l	HETP^a cm
1	100	1870	0.548	0.81
2	200	950	0.200	11.4
3	300-400	360	0.206	1.17
4	280	120	0.208	0.62

[a] Height equivalent to a theoretical plate.

Resin 1 is a commercial macroporous resin (Duolite A161, Rohm and Haas) with quaternary ammonium groups prepared from chloromethyl resin and trimethylamine. Its DVB contents is moderate. Resin 2 is also a macroporous commercial resin (XAD4, Rohm and Haas) with a high DVB content and a high surface area. Resin 3 was prepared from macroporous S-DVB with limited DVB content (13 %) and having only large pores. (A high amount of non-solvent diluent, 65 % benzyl alcohol was used in the synthesis of the resin so that it belongs to domain III in Fig. 2.) Then a post-copolymerization of dimethylaminoethyl methacrylate followed by quaternization with dimethyl sulfate was carried out, the resin being finally used with Cl$^-$ counterion. Resin 4 is a pellicular resin prepared by grafting vinylbenzyl chloride onto perixidized polypropylene beads and subsequent quaternization.

Some other characteristics of these resins are reported in Table 5.

It is clear that the accessibility of resins 3 and 4, which are not crosslinked (or very slightly, resin 3) and the functional groups of which are essentially grafted onto an inert support, is much better than that of the commercial resins. For these resins, the slope of the curve (and hence the exchange rate) is very steep but their capacity is limited, chiefly in the case of resin 4. Resin 2 shows two kinds of sites. Part of them, most probably located on or near the surface, is reasonably accessible. This part is important because the surface area of the resin is high. However, the long tail for high E values indicates the presence of sites more and more difficult to be reached (probably due to diffusion through small pores). Resin 1 is of interest for high capacity coupled with a rather reasonable accessibility. However, it must be recalled that the diameter of its beads is much lower than that of the other resins, so that the dead volume, which is responsible for radial diffusion of the eluted species is correspondingly more limited. Smaller sizes of resins 2-4 should lead to improved accessibility.

However, there is an obvious drawback of the more accessible supports: their capacity is limited and in most of the applications a compromise must be found between accessibility and capacity. In the author's opinion, one of the best compromises should be obtained with resins like resin 3. Yet, their mechanical properties have to be improved, because the resins are too brittle and in a number of conditions may explode in very fine particles.

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