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Tailoring of 4-Vinylpyridine-Based Resins for Hydrolytic Degradation and Solubilisation

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Abstract

Gel-type and macroporous 4-vinylpyridine-derived polymer resins have been prepared by suspension polymerisation employing ethylene glycol diacrylate, ethylene glycol dimethacrylate or divinylbenzene as the crosslinker. Each resin has also been converted into its pyridinium ion form via methylation using methyl iodide, in effect producing the corresponding anion exchange resins. The hydrolytic stability under both acidic and alkaline conditions of both the neutral and the cationic forms of all the resins has been assessed. Crosslinks derived from the diacrylate monomer are the most hydrolytically labile whereas the dimethacrylate derived crosslinks cleave only under basic conditions and when the resin is in its quaternised form. Remarkably a gel-type resin lightly crosslinked using divinylbenzene also degrades under similar conditions, and since the crosslink itself is likely to be stable it seems that mainchain scission is involved in this instance.

Keywords: degradation; polymer supports; pyridine; resins

Introduction

Synthetic ion exchange resins based on crosslinked suspension polymerised resins or beads derived from styrene or methacrylate monomers have become vital materials in terms of water treatment (ground, river and waste), steam turbine condensate polishing, primary and secondary metal ion extraction and recovery, nuclear processing and reprocessing, catalysis (sulfonic acid resins) and sugar purification. [1] Increasingly, however, these species are now being employed in synthetic organic chemistry as supports for reactive anions and cations (oxidants, reductants, nucleophiles) [2] or to immobilise catalytic species (phase transfer catalysts and charged metal complex catalysts). [3-6] There is also growing interest in the use of these and related species in facilitating the work-up and isolation of products, or the removal of by-products from organic reactions. [7-9] While the intrinsic insolubility and heterogeneous nature of these species provides the immediate benefit in the above applications, there are situations where it may be convenient to be able to solubilise the ion exchange at will, for example, to facilitate recovery of a species which cannot be eluted by routine methods or to allow homogeneous

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assay of some polymer-bound functionality. In this paper we describe the synthesis and evaluation of 4-vinylpyridine (4VP)-based resins and the anion exchange species derived therefrom, designed to be hydrolytically degradable to water-soluble fragments.

Results and discussion

1. Suspension polymerisations

Five resins RI-V were prepared by suspension copolymerisation (Figure 1) using the co-monomer feed compositions shown in Table 1. RI, RII and RIII were crosslinked with 2 vol% ethylene glycol diacrylate (EGDA), ethylene glycol dimethacrylate (EGDMA) and divinylbenzene (DVB) respectively. Each of these was prepared in the absence of any porogen and so all are gel-type resins [10]. The N_2 BET surface area of each is ~1 m^2 g^{-1} confirming the absence of any porosity in the dry state. RIV was prepared using 20 vol% ethylene glycol diacrylate and RV with 25 vol% divinylbenzene. The former used 2-ethylhexan-1-ol as a porogen and the latter dodecan-1-ol (each 1:1 v/v relative to monomers). These formulations would be expected to produce a macroporous morphology [10] and indeed the N_2 BET surface area of RIV is 21 m^2 g^{-1} and of RV is 61 m^2 g^{-1} confirming the permanent dry state porosity of both of these species. The yield of high quality beads was ~75% for RI, RIV and RV, and ~95% for RII and RIII. The diameter range for RI was 200-1000 μm and 75-700 μm for the other samples. A mid fraction of each (Table 1) was selected for further study.

The FTIR spectra of the samples were as expected, with the aromatic C=N band at ~1930-1940 cm^{-1} and RI and RII and RIV displaying a strong C=O band at ~1720-1735 cm^{-1}.

The elemental microanalytical data for the samples (Table 1) show reasonable agreement with the theoretical values calculated assuming that each resin composition is identical to the co-monomer feed. In practice the N% content is consistently a little lower than the theoretical, possibly due to a disproportionate loss of 4-vinylpyridine to the aqueous phase in which it has higher solubility than the other co-monomers. The variation, however, is within the limits normally seen in suspension polymerisations. The pyridine group content in each resin is therefore essentially as designed.

2. Methylation of resins and ion exchange of the resultant quaternary pyridiniumiodides

The rapid progress of each methylation reaction (Figure 1) was apparent in a colour change with each resin from light brown to bright yellow. The latter is due to a charge transfer transition associated with the pyridinium iodide functionality. The FTIR spectra of the product resins RI-VQ also show a shift in the C=N absorption to 1650 cm^{-1} characteristic of the N-methylated pyridine ring. The elemental microanalytical data for the quaternised resins again show reasonable agreement with the theoretical predictions (Table 1). The largest and most consistent discrepancy arises with the I% content, typically being 8-25% below the anticipated figures. This is almost certainly indicative of incomplete methylation. Perhaps not surprisingly the two macroporous resins RIVQ and RVQ show the highest level of alkylation and

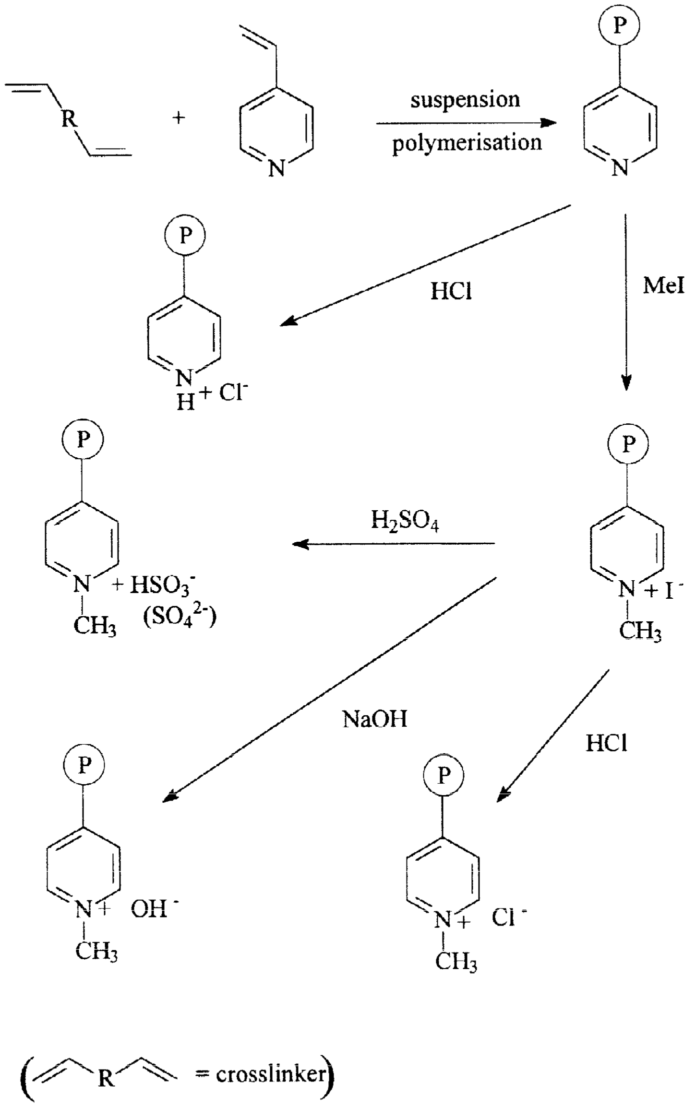

Figure 1 Synthesis, methylation and ion exchange of 4-vinylpyridine based resins

is indicative of good reagent penetration. The divinylbenzene crosslinked gel-type species RIIIQ shows the lowest degree of quaternisation and suggests that the other (meth)acrylate-type crosslinkers offer better swelling in analogous resins utilising these crosslinkers under the reaction conditions employed. Since the methylation process converts an uncharged resin into a fully charged (salt-like) one, choice of an optimum solvent can be problematical in that a relatively hydrophobic medium is required initially, whereas protonic solvents (*e.g.* CH_3OH) would be expected to swell the final resin more effectively. Acetone was chosen as a compromise in this case, and bearing in mind that all these reactions were run at room temperature, the level of chemical modification achieved is good. Furthermore, for the present study no attempt was made to optimise the methylations by, for example, running reactions at elevated temperature.

In order to confirm that all the methylated species were indeed effective anion exchange resins each was treated in a small column with excess dilute H_2SO_4 to displace the I^- counterion (Figure 1). The dried resins were again subjected to elemental microanalysis to assess the level of exchange and since a colour change from bright to dull yellow was apparent in all cases this looked optimistic. The S% contents of the exchanged resins are shown in Table 1. In the case of RI-IIIQ the residual iodine content was 0%, while from R-IVQ and R-VQ it was 2.5 and 0.6% respectively. Interestingly therefore, the three lightly crosslinked gel-type resins undergo anion exchange very efficiently in water, whereas the more heavily crosslinked macroporous resins show marginal incomplete exchange under the conditions used here. This suggests that a small number of ion exchange sites are relatively inaccessible and probably situated in locally hydrophobic environments. Overall, however, the exchange process is efficient and the mole ratio of S:N in each resin is close to 1:1, and certainly not 1:2. Since the I^- content is also very small or zero, the overwhelmingly predominant anion present must be HSO_3^- rather than SO_4^{2-}.

Table 1 Synthesis of 4-vinylpyridine-based resins

Resin	Composition[a]	Bead[b] size used (μm)	Elemental microanalytical data (%): Found (Theoretical)					Functional group loading (mmol g^{-1}): Found (Theoretical)		
			C	H	N	I	S[c]	Based on N%	Based on I%	Based on S%[c)]
RI	2% EGDA/ 97% 4VP (G)	400-700	74.8	6.9	11.5	--	--			
			(79.2)	(6.7)	(12.9)			8.2 (9.2)	--	--
RII	2% EGDMA/ 98% 4VP (G)	100-200	73.8	7.1	11.8	--	--			
			(79.2)	(6.8)	(12.8)			8.4 (9.2)	--	--
RIII	2% DVB/ 98% 4VP (G)	200-300	77.3	6.8	12.0	--	--			
			(80.2)	(6.8)	(13.0)			8.5 (9.3)	--	--
RIV	20% EGDA/ 72% 4VP (M)	300-400	68.5	6.6	8.6	--	--			
			(73.2)	(6.5)	(9.5)			6.1 (68)	--	--
RV	25% DVB/ 69% 4VP (M)	300-400	79.1	7.0	9.8	--	--			
			(82.9)	(7.0)	(10.2)			7.0 (7.3)	--	--
RIQ	2% EGDA/ 97% 4VP (G)	400-700	39.6	4.7	5.5	43.2	13.3			
			(39.1)	(4.1)	(5.6)	(50.6)	(14.6)	3.9 (4.0)	3.4 (4.0)	4.1 (4.6)
RIIQ	2% EGDMA/ 98% 4VP (G)	100-200	41.6	4.9	5.6	43.4	13.5			
			(39.2)	(4.1)	(5.6)	(50.5)	(14.5)	4.0 (4.0)	3.4 (4.0)	4.2 (4.5)
RIIIQ	2% DVB/ 98% 4VP (G)	200-300	44.5	5.1	6.6	36.8	12.4			
			(39.5)	(4.1)	(5.6)	(50.8)	(14.6)	4.7 (4.0)	2.9 (4.0)	3.9 (4.6)
RIVQ	20% EGDA/ 72% 4VP (M)	300-400	40.9	4.6	4.3	38.2	12.5			
			(41.5)	(4.4)	(4.8)	(43.8)	(12.3)	3.1 (3.4)	3.0 (3.4)	3.9 (3.9)
RVQ	25% DVB/ 69% 4VP (M)	300-400	43.4	4.6	4.6	41.1	12.1			
			(45.1)	(4.5)	(5.0)	(45.4)	(12.8)	3.3 (3.6)	3.2 (3.6)	3.8 (4.0)

[a] Vol% of actual crosslinker, calculated from purity of technical grade; G = gel-type; M = macroporous

[b] Bead yield ~75% for RI, RIV, RV; ~95% for RII, RIII; Full diameter range; 200-1000 μm, RI; 75-700 μm;

[c] RII-V

3. Hydrolytic degradation studies

Table 2 summaries all the gravimetric data from the degradation studies, and before evaluating these it is important to bear in mind the gravimetric changes anticipated simply from the anion exchange processes that might occur with NaOH and HCl.

As far as the non-quaternised resins RI-V are concerned treatment with aqueous NaOH would not be expected to cause any mass change since anion exchange is not possible. With aqueous HCl however all the resins can be protonated (Figure 1) and the theoretical mass increases with the formation of pyridinium hydrochloride are shown in Table 2. In the case of the quaternised resins RI-VQ dilute NaOH might be expected to displace I^- with OH^- with the predicted loss of mass shown in Table 2. Likewise dilute HCl might displace I^- with Cl^- with the anticipated loss of mass shown in Table 2. All experimentally determined changes in mass must be considered in the context of the above.

Table 2 Hydrolytic degradation of 4-vinyl pyridine-based resins

	Hydrolysis with 2M NaOH				Hydrolysis with 2M HCl			
Resin	Initial mass (g)	Change in mass (g)	Mass change (%)	Theoretical mass change due to ion exchange (%)	Initial mass (g)	Change in mass (g)	Mass change (%)	Theoretical mass change due to ion exchange (%)
RI	0.1045[a]	-0.1045	-100[b]	--	0.1155	-0.0668	-58	+30[c]
RII	0.1037[a]	-0.0084	-8	--	0.1175	+0.0286	+24	+31[c]
RIII	0.1062[a]	-0.0074	-7	--	0.1036	+0.0027	+3	+31[c]
RIV	0.1016[a]	-0.1016	-100[b]	--	0.1163	+0.0103	+10	+22[c]
RV	0.1028[a]	-0.0073	-7	--	0.1051	+0.0298	+28	+26[c]
RIQ	0.1000[d]	-0.0900	-90	-37[e]	0.1000	-0.0305	-31	-31[f]
RIIQ	0.1000[d]	-0.0880	-88	-37[e]	0.1000	-0.0371	-37	-31[f]
RIIIQ	0.1050[d]	-0.0989	-94	-31[e]	0.1020	-0.0342	-34	-26[f]
RIVQ	0.1000[d]	-0.1000	-100[b]	-23[e]	0.1000	-0.0369	-37	-27[f]
RVQ	0.100[b]	-0.0030	-32	-35[e]	0.1004	-0.0199	-20	-29[f]

[a] Neutral pyridine-based
[b] Complete dissolution
[c] Due to protonation by HCl
[d] I^- form of methylated resin
[e] Due to ion exchange $I^- \rightarrow OH^-$
[f] Due to ion exchange $I^- \rightarrow Cl^-$

Considering first the non-quaternised resins RI-V with NaOH (Table 2), it is clear that both RI and RIV undergo complete hydrolysis even under the room temperature conditions of the experiment. The crosslinker in both of these resins is ethylene glycol diacrylate and in the case of both the gel-type species RI, and the macroporous species RIV, the acrylic ester is very readily cleaved, possibly with pendant pyridine groups acting cooperatively with OH^- This behaviour is consistent with that of CLEAR resins described recently for use in solid phase peptide synthesis [11] where these resins despite being highly crosslinked using an ethoxylate triacrylate nevertheless underwent ready degradation under strongly basic conditions. The other neutral resins RII, RIII and RV show only a minor reduction in mass almost certainly accounted for by handling losses. RIII and RV are crosslinked by divinylbenzene residues and so their stability is readily understood. RIV on the other hand utilises ethylene glycol dimethacrylate as the crosslinker, and clearly the sterically more hindered methacrylate ester is much more stable than the analogous acrylate ester. This difference is well recognised by ion exchange resin manufacturers and indeed Fréchet *et al* [12] have similarly reported 4-vinylpyridine resins crosslinked with this dimethacrylate to be base stable in the neutral form.

In the presence of dilute HCl the non-quaternised resins RII-V show a mass increase in keeping with formation of the corresponding pyridinium chlorides. With RII and RV there is reasonably good agreement with the theoretical mass increase based on full protonation and it seems that the dimethacrylate crosslinked gel-type species RII, and the macroporous divinylbenzene crosslinked resin RV both allow ready access of the matrix to dilute HCl. For RIII the increase in mass is very small and almost certainly reflects the poor compatibility of this gel-type divinylbenzene crosslinked resin with aqueous acid. Increase in reaction time or higher temperature would almost certainly lead to much improved protonation. The modest increase in mass displayed by the macroporous diacrylate crosslinked species RIV may well represent a balance between the increase in mass arising from hydrochloride salt formation and the loss of mass resulting from partial hydrolytic cleavage and degradation. The latter is quite apparent in the case of RI where the experimental mass change is a loss of 58%, representing very significant degradation and solubilisation of the lightly diacrylate crosslinked gel-type species.

In summary therefore as far as the non-quaternised resins are concerned RII and RV display the best stability in both aqueous acid and base, coupled with good exchange/protonation behaviour. In contrast the diacrylate crosslinked resins RI and RIV both degrade completely in base with RIV showing reasonable stability in acid.

Very contrasting behaviour is observed with some of the quaternised resins RI-VQ. In aqueous base simple ion exchange of OH^- replacing I^- would predict a mass loss in the range ~25-35% depending on the resin (Table 2). In practice RI-IVQ show very substantial degradation with RIVQ completely dissolving. The facile hydrolytic cleavage of the diacrylate esters in RIQ and RIVQ is consistent with the behaviour displayed by RI and RIV in aqueous base. Superficially more surprising is the extensive degradation and solubilisation of RIIQ under conditions when RII is stable. However, Fréchet *et al* [12] have already reported that 4-vinylpyridine-based resins in their quaternised form and crosslinked by dimethacrylate derived esters, though acid stable, undergo facile base hydrolysis, and they have shown fairly conclusively that an intramolecular mechanism involving pyridinium methide units play a key role (Figure 2). The present results confirm these earlier findings. What remains most remarkable however is the behaviour of resin RIIIQ which also undergoes almost complete degradation and solubilisation. This is despite the crosslinks being derived from divinylbenzene. We are unaware of any earlier report of these linkages being labile under the present conditions and can offer no suggestion of a plausible mechanism. On the other hand it is possible to speculate how backbone cleavage of adjacent vinyl pyridinium residues might occur (Figure 3) under aqueous base conditions. Again the first step would be formation of the pyridinium methide followed by re-aromatisation and simultaneous mainchain scission. With a lightly crosslinked resin such as RIIIQ the divinylbenzene-derived crosslinks might therefore remain intact, with degradation and dissolution being driven by cleavage of the main spine of network. This mechanism would also explain why the more heavily crosslinked macroporous resin derived from divinylbenzene, RVQ, remains stable and displays a mass loss more or less equivalent to that predicted by the I⁻ → OH⁻ exchange alone. For this resin to degrade sufficiently to display some solubility many more chain scissions would be required to disconnect the crosslinked network sufficiently. In addition, with at least 25% of the backbone residues being non-pyridinium ion in nature *i.e.* derived from the divinylbenzene feed, fewer pyridinium salt residues will be found adjacent to each other to allow the mechanism shown in Figure 3 to operate.

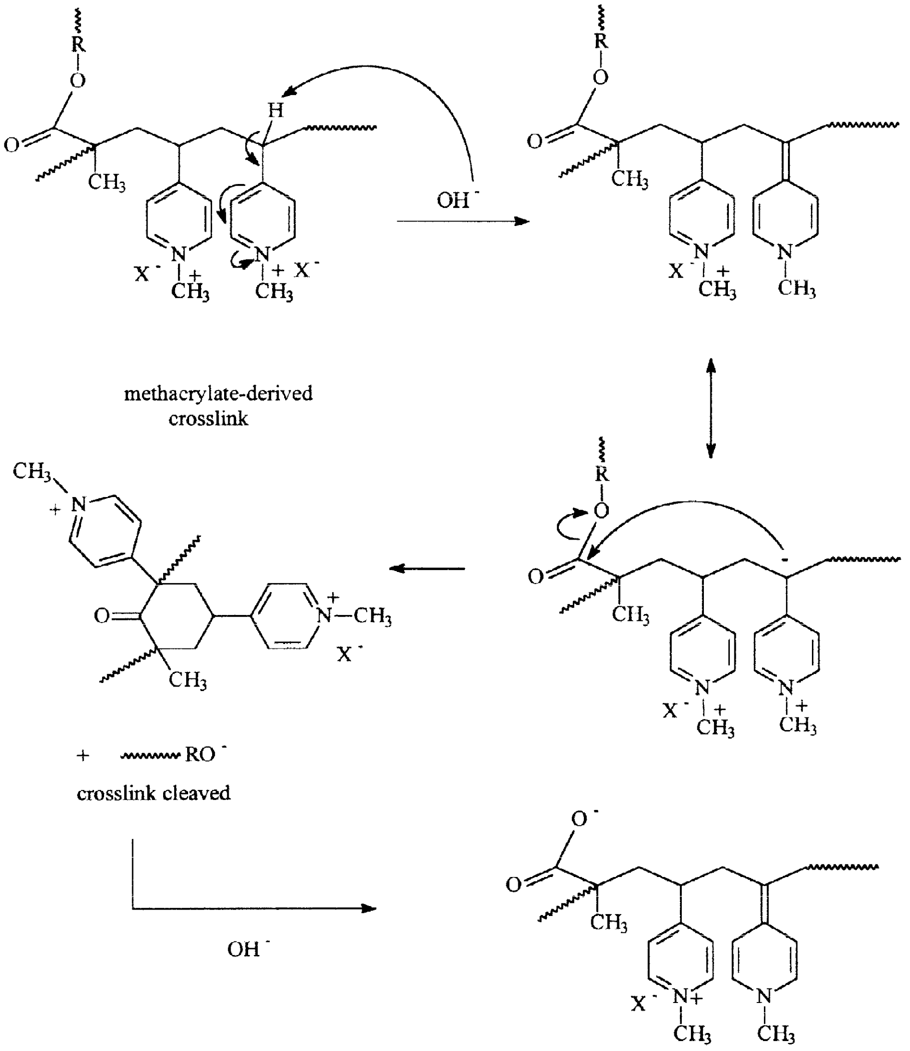

Figure 2 Proposed intramolecular ester cleavage mechanism involving pyridinium methide units in quaternised 4-vinylpyridine-based resins [12]

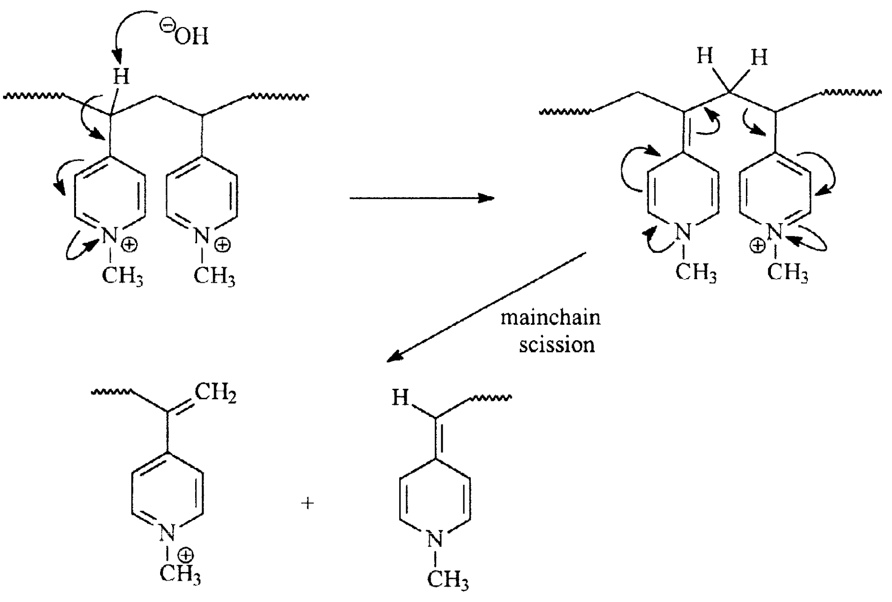

Figure 3 Possible mechanism for scission of polymer mainchain in methylated 4-vinylpyridine derived resins

When the quaternised resins RI-VQ are treated with aqueous HCl the mass loss observed corresponds roughly with the mass change expected when I^- is replaced by Cl^-. Somewhat surprisingly even RIQ seems stable in acid, and this probably arises because of repulsion of the H^+ by the cationic pyridinium ion resin. This behaviour is similar to that seen when ionic reactions are performed in the presence of linear soluble polyelectrolytes [13]. A cationic polyelectrolyte, for example, will accelerate the reaction between two anionic species, but will retard one involving an anionic and cationic reactant as a result of selective repulsion of the latter and selective attraction of the former.

Table 3 Summary of hydrolytic stability data for 4-vinylpyridine-based resins

Crosslinker	Neutral form of resin		Cationic form of resin	
	acidic conditions	basic conditions	acidic conditions	basic conditions
diacrylate ester	X	X	✓	X
dimethacrylate ester	✓	✓	✓	X
divinylbenzene (low)	✓	✓	✓	X
divinylbenzene (high)	✓	✓	✓	✓

✓ = stable; X = unstable/degradable

Conclusion

4-Vinylpyridine-derived resins with specific hydrolytic stability properties have been designed and synthesised. For resins to be stable in both their neutral and cationic forms at all pH values, it is essential to use a high level (*ca* >20%) of divinylbenzene as the crosslinker with the resin in a macroporous morphology to allow good accessibility. Entries in Table 3 summarise the overall hydrolytic stability properties as a function of: i) the structure of the chosen crosslinker; ii) whether the resin is to be applied in its neutral or cationic alkylated form, and iii) the conditions of the hydrolytic reaction. From this Table it is possible to select a particular resin for a specific application.

Experimental

1. Materials

4-Vinylpyridine (4-Vpy) (95%), divinylbenzene (DVB) (80% 1,3- and 1,4-DVB, 20%, 3- and 4-ethylstyrene), ethylene glycol diacrylate (EGDA) (70%); ethylene glycol dimethacrylate (EGDMA) (98%), 2-ethylhexan-1-ol and dodecan-1-ol were used as supplied from the Aldrich Chemical Co. Azobisisobutyronitrile was also used as bought from the BDH Co.

2. Suspension polymerisation (Figure 1)

Each resin was prepared by suspension polymerisation as already reported in detail [14]. The aqueous phase was of 600 cm^3 and the organic phase 50 cm^3 with AIBN employed at 1 wt% of monomers. The level of crosslinker employed was calculated as a vol% accounting for the purity of the technical grade materials (see Table 1). In the case of the macroporous resins RIV and RV, the porogen used was 2-ethylhexan-1-ol and dodecan-1-ol respectively in a volume ratio to monomers of 1:1. Polymerisations were carried out under N_2 at 80°C for 5 h. The polymer beads were collected by filtration and washed copiously with distilled water, then methanol and diethyl ether. The air dried beads were then extracted with acetone in a Soxhlet apparatus overnight and finally vacuum dried at 50°C. The dry beads were divided into fractions by size sieving, and appropriate central fractions (Table 1) combined for elemental microanalysis and further chemical manipulation.

Compositional and elemental microanalytical data are summarised in Table 1.

3. Methylation of resins (Figure 1)

Samples of each resin (RI-V) (~2 g) were placed in 20 cm^3 vials. To each vial iodomethane (2.5 cm^3, ~2 equiv.) was added, followed by acetone (15 cm^3). Each vial was then sealed and shaken at room temperature for 40 h. All the products RI-VQ were extracted with acetone in a Soxhlet apparatus overnight then vacuum dried at 50°C before being subject to elemental microanalysis (Table 1).

4. Ion exchange with H_2SO_4 (Figure 1)

A pasteur pipette was packed with polymer resin (RI-VQ) and employed as a small ion exchange column. Dilute H_2SO_4 (0.1M) was run through the column until 50 cm^3 of eluent was collected. The column was then eluted with distilled water and acetone before the resin was removed and vacuum dried at 50°C overnight before being subjected to elemental microanalysis (Table 1).

5. Hydrolytic degradation studies

A sample (~ 0.1 g) of each original resin RI-V and each methylated resin RI-VQ was placed in dilute HCl (2M, 15 cm^3) and dilute NaOH (2M, 15 cm^3) and shaken for 8 days at room temperature. Each sample was recovered by filtration, washed with deionised water and acetone, and vacuum dried at 50°C. Each recovery was carried out as quantitatively as possible, and residues determined gravimetrically. The results are shown in Table 2.

6. Instrumentation

FTIR spectra of samples as KBr discs were recorded on a Nicolet Impact 400D spectrometer. Resin surface areas were calculated from N_2 sorption isotherms generated using a Micromeritics ASAP2000 gas sorption instrument; the BET treatment was employed [15].

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