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Transesterification of Benzyl Phenylacetate Using Polymeric Quaternary Ammonium Salt of 1,8-Diazabicyclo[5.4.0]undec-7-ene

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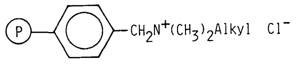
When benzyl phenylacetate was treated with aqueous alcohols in the presence of polymer-attached quaternary ammonium hydroxide (PCS–DBU) prepared from 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) and chloromethylated polystyrene, the transesterification to methyl phenylacetate preceded the hydrolysis to phenylacetic acid. The characterization of this PCS–DBU resin was studied by comparison with other analogous resins. It was found that the PCS–DBU resin has the highest catalytic activity and the strongest attractive affinity to the substrate among the three resins studied in this work, and plays an important role in the formation of alkoxide ions by the reaction of alohols with the hydroxide ions above the resin, in the protection of the alkoxide ions against the attack of water molecules, and in the attraction of the substrate. These effects were attributed to the specific and planar bicyclic system of the DBU, including hydrophobic long alkylene groups, in addition to the lipophilic function of polymeric skeleton. The reaction could be explained in terms of the mechanism of phase-transfer catalysis.

Extensive studies on the role of ion-exchange resins in acid-base reactions have been reported. Strongly basic anion exchange resins were active as a catalyst in the Aldol and Knoevenagel condensations, cyanoethylation, and so on.[1–3] Little is known concerning studies on the hydrolysis[4] and transesterification[5] of esters by anion exchange resins, compared with those by cation exchange resins.[6] On the other hand, a variety of organic reactions have been reported to be catalyzed by tetraalkylammonium salts,[7] and the hydrolysis of esters in aqueous sodium hydroxide is among their reactions. Insoluble phase-transfer catalysts linked to a polymer matrix were first described by Regen,[8] and polymeric tetraalkylammonium salts **1** were used in a wide series of anion-promoted reactions.



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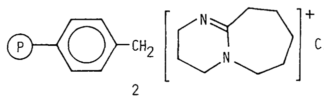

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It was described in a previous paper[9] that the polymer-supported quaternary ammonium salts **2** linked 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) to chloromethylated polystyrene were synthesized, and a free base form of the polymer (PCS–DBU) has low reactivity for chloride and sulfate ions. This fact indicates that the hydroxide ions are strongly attracted to the quaternary ammonium cations to form ion pairs on the polymer. Because the DBU residues linked to the resin are composed of a planar bicyclic system with included hydrophobic alkylene groups, we expected the characteristically catalytic function of the PCS–DBU resin. In this study, when benzyl phenylacetate was treated with methanol-water mixtures in the presence of the PCS–DBU resin, it was found that transesterification to methyl phenylacetate precedes hydrolysis to phenylacetic acid. This paper therefore describes the effect of the PCS–DBU resin on the reaction, compared with other analogous resins.

Experimental

Materials. Quaternary ammonium polymers were prepared by the amination of chloromethylated polystyrene with DBU, trimethylamine, and triethylamine, respectively, according to a method described in a previous paper.[9] Chloromethylated polystyrene were prepared by chloromethylation of 2% divinylbenzene–styrene copolymer (200—400 mesh; Eastman Kodak Co.) according to Refs. 10 and 11. Commercial DBU (Extra pure; Sanyo Kasei Kogyo Co.) was purified by distillation; bp 88—89 °C (400 Pa). Benzyl phenylacetate was washed with water, dried on calcium chloride, and distilled; bp 175—177 °C (3200 Pa). Other chemicals of reagent grade were used without further purification.

Preparation of Free Base Form Resins. The quaternary ammonium chloride forms of the resins were treated with 2M sodium hydroxide (1M=1 mol dm^{-3}), and then recovered by filtration. The resin was washed with water, dried in vacuo and submitted to analysis and subsequent reaction.

Determination of Ion-Exchange Capacities. The ion-exchange capacity was calculated from the amounts of hydrochloric acid reacting with the free base form resins according to the general method[12] for the total ion-exchange capacity.

General Procedure for Reaction of Benzyl Phenylacetate in Aqueous Alcohols. In a 200-cm^3 round-bottomed flask equipped with a stirrer, a reflux condenser, and a thermometer were placed 1.2 mmol of benzyl phenylacetate and 50 cm^3 of 30% methanol–water mixtures; to this, 0.26 mmol (converted to hydroxide ion) of the free base forms of resins was added. The reaction was carried out at 60 °C. After a given time, some part of this mixture was removed and the detection of the substrate and products was performed by a GLC equipped with a Silicone OV-17 chemically bonded capillary column (25 m).

Determination of the Amount of Compounds Attached to the Resins. In 30% methanol-water mixtures involving 0.28 mmol of benzyl phenylacetate, methyl phenylacetate, or benzyl alcohol was added 0.26 mmol (converted to the DBU quaternary ammonium group) of chloride form of the PCS-DBU resin. The treatment was carried out at 60 °C. During every prescribed time interval, the concentrations of the solutes were determined by GLC, in the same way as described above.

Determination of the Degree of Swelling. Into a 10-cm^3 graduated cylinder was placed a weighed quantity of the dry resin (W/g); its volume (V_1/cm^3) was then measured; to this, 5 cm^3 of distilled water was added. The mixture was allowed to stand for 2 days at room temperature with occasional outgassing under ultrasonic vibration, and the volume (V_2/cm^3) of the swelling resin was measured. The degree of swelling (V_s/cm^3 g^{-1}) was determined using

$$V_s = (V_2 - V_1)/W.$$

Results and Discussion

Reaction in Methanol-Water Mixtures. When benzyl phenylacetate was treated with 30% methanol-water mixtures in the presence of the PCS-DBU resin, benzyl alcohol and methyl phenylacetate were produced. Along with the hydrolysis of benzyl phenylacetate proceeds; though phenylacetic acid should be formed, it was not detected. The reaction of phenyl benzoate in a similar manner produced methyl benzoate and phenol, indicating that the degree of hydrolysis was negligibly small. The reaction of phenyl benzoate with ethanol in the presence of sodium hydroxide can be formulated as follows:

$$C_6H_5COOC_6H_5 + NaOH \longrightarrow C_6H_5COONa + C_6H_5OH \quad (1)$$

$$C_2H_5OH + NaOH \rightleftharpoons C_2H_5ONa + H_2O \quad (2)$$

$$C_6H_5COOC_6H_5 + C_2H_5ONa \rightleftharpoons C_6H_5COOC_2H_5 + C_6H_5ONa \quad (3)$$

However, it is known that the reaction rate of Eq. 3 is about 1000-times faster than that of the reaction of Eq. 1.[13] In spite of the reaction in alcohol-water mixtures, the result obtained in this study was similar to that described above. The results of the reaction of benzyl phenylacetate are shown in Figs. 1 and 2. As can be seen from Fig. 1, the difference between the yield of methyl phenylacetate and that of benzyl alcohol was observed, and a material balance was unsatisfactory. Figure 2 shows the effect of the reaction temperature. In Figs. 1 and 2, it can be assumed that a decrease in the concentration involves an additional change owing to lipophilic/hydrophobic interaction between the resin and the solutes. Therefore, in order to determine the degree of its interaction, variations in the concentration of benzyl phenylacetate, methyl phenylacetate, and benzyl alcohol with time in the presence of the same amount of chloride form of the PCS-DBU resin as that of addition for the transesterification in 30% methanol-water were investigated. The result is shown in Fig. 3. The adsorption noted in this figure was represented by the percentage decrease in the quantity of solutes. From these results, it was found that the solutes are fully adsorbed by the resin, and within 60 minutes the adsorption attains in every solute equilibrium fairly rapidly. The degree of adsorption by the resin increases with an increase in the hydrophobic affinity of the compounds. From this result, it became apparent that there is appreciable interaction between the resin and solutes. The interaction seems to result from the lipophilic effect of the carbon skeleton in the main-chain of the resin and

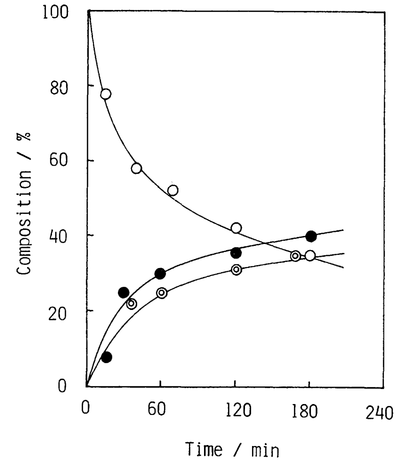

Fig. 1. Transesterification of benzyl phenylacetate with 30% methanol-water mixtures at 60 °C in the presence of the PCS-DBU Resin. ○: Benzyl phenylacetate; ●: benzyl alcohol; ◎: methyl phenylacetate.

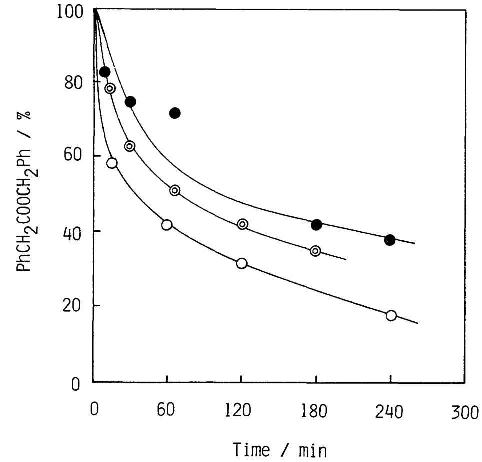

Fig. 2. Effect of reaction temperature in the transesterification of benzyl phenylacetate. ●: Data at 42 °C; ◎: data at 60 °C; ○: data at 70 °C.

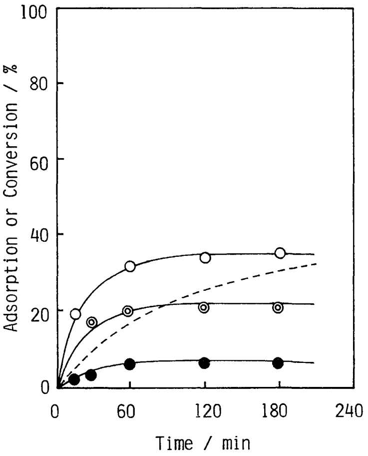

Fig. 3. Adsorption of benzyl alcohol (●), methyl phenylacetate (◎), and benzyl phenylacetate (○) on chloride form PCS-DBU resin. Dotted curve shows the corrected conversion of benzyl phenylacetate in the presence of free base form PCS-DBU resin.

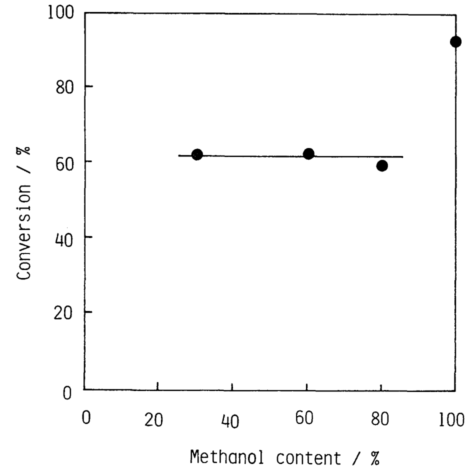

Fig. 4. Effect of methanol content on the conversion at 150 min in the transestérication of benzyl phenylacetate at 60 °C in the presence of the PCS-DBU resin.

some effect of the DBU residues anchoring in the side-chain of the resin. Consequently, when the value of the adsorption obtained in Fig. 3 was subtracted from the conversion of benzyl phenylacetate in the transesterification determined in Fig. 1, the time dependence of its corrected conversion could be depicted by the dotted curve in Fig. 3; further, an increase in the conversion obeyed good first-order kinetics. Similarly, benzyl alcohol and methyl phenylacetate were produced in an approximately equal ratio.

Sodium alcoholate is usually used in transesterification. In alcohol-water mixtures, however, the esters are hydrolyzed with hydroxide ion which is formed by the reaction of alkoxide ions with water molecules. Figure 4 shows the dependence of the methanol content on the conversion for benzyl phenylacetate. As can be seen from this figure, in absolute methanol conversion attained a 90% level after 150 minutes. In methanol-water mixtures, however, the value was only 60% under the same conditions, and was independent of the methanol composition. Such similar behavior was observed in the relation between the methanol content and the selectivities of methyl phenylacetate and benzyl alcohol.

For a comparison with catalysis by a resin, benzyl phenylacetate was treated with 60% methanol-water mixtures at 26 °C in the presence of 0.26 mmol of sodium hydroxide. The results are shown in Fig. 5. After the transesterification to methyl phenylacetate was rapidly and favourably completed, the selectivity of methyl phenylacetate decreased gradually to a low value because of a secondary hydrolysis. In contrast with the above result, such secondary hydrolysis was not observed for a reaction in the presence of the PCS-DBU resin.

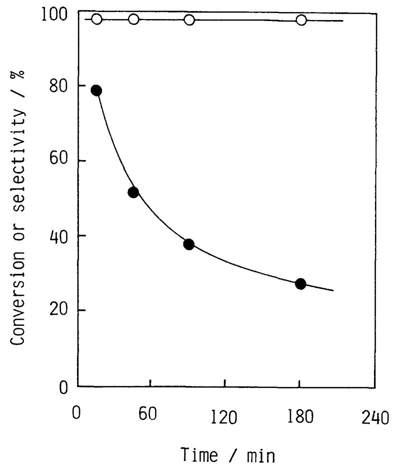

Fig. 5. Change in distribution of substrate and products in the transesterification of benzyl phenylacetate (1.2 mmol) with 60% methanol aq solution (50 cm^3) at 26 °C in the presence of sodium hydroxide (0.26 mmol). ○: selectivity of benzyl alcohol and conversion of benzyl phenylacetate; ●: selectivity of methyl phenylacetate.

Catalytic Activity of the PCS-DBU Resin. As described above, reactions in methanol-water mixtures were troublesome. Therefore, the dependence of conversion on the charge of the resin for benzyl phenylacetate was studied in absolute methanol. The results are shown in Figs. 6 and 7. A catalysis cyclic system was observed from the results shown in Fig. 6. As can be seen from Fig. 7, the selectivity of benzyl alcohol produced was over 90% during the early stages of the reaction in the presence of substrate, over 5-times that of the resin. Further, this reaction could be treated as first-order kinetics. Consequently, the chemical reactivities of alcohols were established by comparisons of the pseudo first-order rate constants for several alcohols. The results are shown in Table 1. The reactivity of the alcohols was of the order methanol>2-methoxyethanol>ethanol>1-propanol. 2-Propanol was unreactive. These results are similar to those of general transesterification, and are understandable on the basis of the electrostatic and steric effects of substituent groups on the methanol molecule.

We expected that the PCS–DBU resin will play specifically because the quaternary ammonium groups on the resin are made up of the DBU residue of planar bicyclic system, including hydrophobic long alkylene groups. Therefore, the transesterification of benzyl phenylacetate in the presence of the PCS–DBU resin was compared with those for the analogous polymeric quaternary ammonium salts anchoring trimethylamine (PCS–TMA) and triethylamine (PCS–TEA). The results studied in absolute methanol are shown in Table 2. From these results, it was found that the PCS–DBU resin has the highest catalytic activity among the three resins studied in this work. As can be seen in Table 2, the degree of quaternization of the

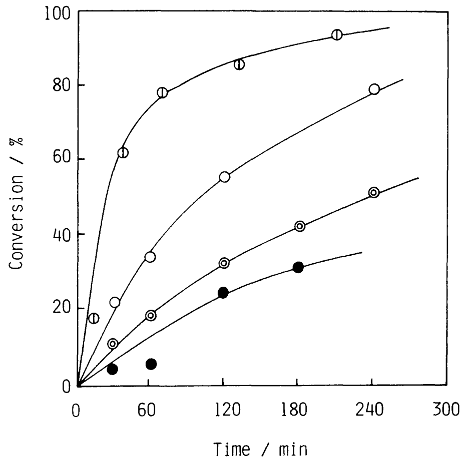

Fig. 6. Effect of substrate/resin molar ratio on the reaction of benzyl phenylacetate in the presence of the PCS–DBU resin. ⦶: Data for 1 : 1 ratio; ○: data for 3 : 1 ratio; ◎ : data for 5 : 1 ratio; ●: data for 10 : 1 ratio.

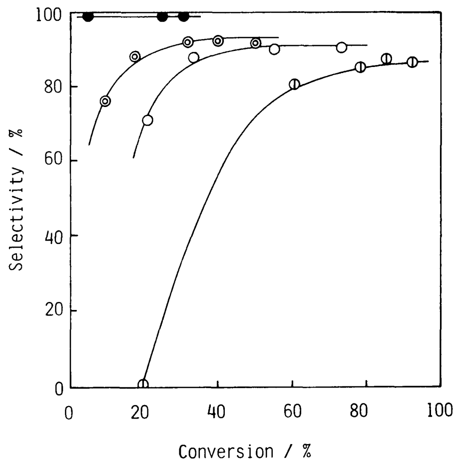

Fig. 7. Relationship between selectivity of benzyl alcohol and conversion of benzyl phenylacetate. For symbols see Fig. 6.

Table 1. Reactivity of Alcohols on the Transesterification of Benzyl Phenylacetate in the Presence of the PCS–DBU Resin

Alcohol	Substrate/Resin molar ratio[a]	k[b] / min^{-1}	Relative reactivity
CH_3OH	5	2.83×10^{-3}	31.4
CH_3CH_2OH	5	9.01×10^{-5}	1.00
$CH_3(CH_2)_2OH$	5	7.00×10^{-5}	0.77
$(CH_3)_2CHOH$	5	Unreactive	—
$CH_3O(CH_2)_2OH$	5	1.16×10^{-4}	1.29

a) Converted to hydroxide ion on the PCS–DBU resin. b) Determined at 60 °C.

Table 2. Additional Effect of Quaternary Ammonium Resins in the Transesterification of Benzyl Phenylacetate with Methanol[a]

Quaternary ammonium resin				Catalytic activity	
Abbreviation	Degree of quaternization[b] / %	Ion-exchange capacity / mequiv g^{-1}	Degree of swelling / cm^3 g^{-1}	k / min^{-1}	Relative activity
PCS–DBU	88.4	1.94	1.01	2.83×10^{-3}	1.00
PCS–TEA	67.1	1.33	0.10	1.37×10^{-3}	0.49
PCS–TMA	59.0	2.46	0.60	2.22×10^{-3}	0.78

a) Reacted in 50 cm^3 of methanol at 60 °C by using 1.2 mmol of benzyl phenylacetate in the presence of 0.26 mmol of hydroxide ion calculated on the basis of ion-exchange capacity for each resin. b) Determined from the yield of quaternary ammonium resin.

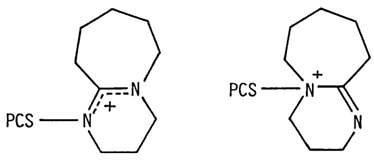

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Fig. 8. Presumed bond-structur of quaternary ammonium group on the PCS-DBU resin.

resins was of the order PCS-DBU>PCS-TMA>PCS-TEA. This order was the same as that of the catalytic activity of the resins. However, because all experiments were carried out in the presence of the same amounts of hydroxide ions (calculated on the basis of the ion-exchange capacity of each resin), the catalytic activity of the resins excludes the possibility of the effect of concentration on hydroxide ion being above the quaternary ammonium groups of the resins. Moreover, the effect of polymer main-chain on catalysis by PCS-DBU seems to be nearly equal to those of PCS-TMA and PCS-TEA, since all of resins studied in this work were prepared from the same chloromethylated polystyrene. Therefore, the difference of catalytic activity owing to the type of resin can be attributed to the property of the amine residues anchoring in the side-chain of each resin. The quaternary ammonium salt of the DBU must be made up of structure **3**, which is more stable than structure **4** because of a resonance (illustrated in Fig. 8). The hydroxide ion as a counterpart ion to the DBU quaternary ammonium cation must be situated in the position of near center above the planar DBU bicyclic system; it will then be less sterically hindered than those of the PCS-TMA and PCS-TEA resins. This seems to be one explanation for the high catalytic of the PCS-DBU resin.

On the other hand, it was found that the percentage of attachment of the solutes to the PCS-TMA resin determined in a similar manner as described for the PCS-DBU resin were 6% for benzyl phenylacetate and less than 1% for methyl phenylacetate and benzyl alcohol, respectively. These values were much lower than that of the PCS-DBU resin. This fact indicates that the catalytic activity of the resin is associated with an affinity to attract a substrate. It is thought that this attraction effect results from a lipophilic interaction between the carbon skeleton in the main chain of the resins and the substrates. As described above, however, because the structure of the PCS-DBU polymer matrix is identical to those of the PCS-TMA and PCS-TEA resins, the lipophilic affinity of the PCS-DBU resin is nearly equal to those of the other resins. Therefore, it is evident that a bicyclic DBU system which includes long alkylene groups, participates largely in the lipophilic attraction of the substrate.

Role of the Resin in Transesterification. According to the mechanism of a phase transfer catalysis, the quaternary ammonium groups on the catalyst exist in either the aqueous[7] or the organic[14] phase; through interface between the aqueous and organic phases the counterpart ion to an ammonium ion is exchanged with the other anions derived from a nucleophile. Consequently, the nucleophile is carried into the organic phase. The reaction formed dibenzyl ether from benzyl chloride in the presence of quaternary ammonium salts in aqueous sodium hydroxide could be explained in terms of a latter mechanism[15] that is operative in the organic phase.

As described above, it appeared that, in aqueous methanol solutions, the PCS-DBU resin well attracts the substrate by lipophilic/hydrophobic affinity. On the other hand, the quaternary ammonium groups of DBU including the hydrophobic alkylene groups may exist in the organic phase without transferring to the aqueous phase. Alkoxide ions, which are taken in the organic phase through the interface, attacks benzyl phenylacetate attached on the organic resin. The reaction mechanism may be interpreted in the form of Eqs. 4—6.

$$\mathrm{PCS\text{-}DBU^{+}\,{}^{-}OH + CH_3OH \rightleftharpoons PCS\text{-}DBU^{+}\,{}^{-}OCH_3 + H_2O} \qquad (4)$$

$$\mathrm{PCS\text{-}DBU^{+}\,{}^{-}OCH_3 + PhCH_2COOCH_2Ph \rightleftharpoons PCS\text{-}DBU^{+}\,{}^{-}OCH_2Ph = PhCH_2COOCH_3} \qquad (5)$$

$$\mathrm{PCS\text{-}DBU^{+}\,{}^{-}OCH_2Ph + H_2O \rightleftharpoons PCS\text{-}DBU^{+}\,{}^{-}OH + PhCH_2OH} \qquad (6)$$

As can be seen in Table 2, the PCS-DBU resin was more swollen than the other resins in water. In the conformational structure for the resins,[16] the swelling of the resins leads to exposure of the quaternary ammonium groups, which are the catalytic active sites in the resins. Therefore, the catalysis increases with an increase in the swelling of the resins. This agreed with data on the reaction rate constant given in Table 2. In Eq. 4, the formation of methoxide ions is inhibited by the addition of water into the reaction mixtures. As illustrated in Fig. 4, however, the conversion of benzyl phenylacetate was independent of the water content. This result is believed to be due to the reaction at or near the interface between the aqueous and organic phases.[17] In absolute methanol, on the other hand, the quaternary ammonium groups is buried into the polymer chains. This results in a greater concentration of catalytic active sites and, consequently, in an increased reaction rate.

In spite of reaction in aqueous solution, the transesterification of benzyl phenylacetate was performed. This is because methoxide ions, which are placed in the hydrophobic reaction fields on the PCS-DBU resin, are protected from the attack of water molecules. As described in a previous paper,[9] hydroxide ions are strongly combined with the quaternary ammonium cations on the PCS-DBU resin. Therefore, the hydrolysis of benzyl phenylacetate with hydroxide ions is more difficult. However, the catalytic activities of the resins are immediately independent of the strength of ionic bonding between the hydroxide ion and the quaternary ammonium ion. Despite such a restriction, hydroxide ions were exchanged with methoxide ions. This is because, in the organic phase, a methoxide ion more easily forms a ion pair with the quaternary ammonium cation than hydroxide ion.[18] If the reaction of Eq. 4 is initiated, the ease of this type of anion exchange should depend on the pK_a value for alcohols. The results represented in Table 1 support this idea.

In addition to benzyl phenylacetate, when benzyl chloride was treated in a similar manner, benzyl methyl ether was selectively produced. This result can be explained in terms of a reaction mechanism similar to that described above. In conclusion, in order to promote the catalytic activity of resins, the attraction of the substrate can be regarded as an important initial step for the reaction. The attraction of the substrates depends on the structure of the amine residues in the quaternary ammonium resins, except for the function of the polymer main-chain. One important characteristic of the PCS–DBU resin is the fact that it has a planar DBU bicyclic system containing a lipophilic/hydrophobic alkylene chain and is less sterically hindered than those of the other resins.

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