Application of Hyperbranched Stationary Phases to Ion Chromatography

by Christopher Pohl
Thermo Fisher Scientific, Sunnyvale, CA 94085, USA

Hyperbranched anion exchange stationary phases are widely used in ion chromatography. Synthetic parameters leading to various selectivities are illustrated. The utility of such materials are demonstrated in a number of application areas including analysis of bromate, perchlorate and phosphate.

Since the introduction of ion chromatography in 1975 by Small et al [1], the development of improved stationary phases for the analysis of inorganic ions and small organic ions has lead to a progressive expansion in the use of ion chromatography in many areas of analytical chemistry [2-4]. Ion chromatography stationary phases based on synthesis techniques that result in hyperbranched stationary phase architectures have been in commercial use for a little more than 10 years [5,6]. Prior to that, most ion exchange stationary phases for Ion Chromatography (IC) were based on polymer architectures utilising radical polymerisation. Although there are some notable exceptions, most such IC stationary phases are based on styrenic monomers or methacrylate monomers. Such materials have the advantage of enabling synthesis of ion exchange stationary phases using relatively inexpensive and easy to polymerise monomers, these two classes of monomers have notable shortcomings when it comes to IC stationary phases. Polymers based on styrenic monomers are noteworthy in terms of their chemical stability, however, stationary phases based on styrenic monomers are relatively hydrophobic. Ion exchange phases designed from such monomers generally allow for good chromatographic performance of highly hydrated ions such as fluoride, chloride and sulphate but tend to exhibit poor peak shape for ions with limited hydration such as perchlorate or iodide. Methacrylate base polymers tend to be significantly more hydrophilic. Methacrylate polymers provide improved peak shape for poorly hydrated polarisable anions such as perchlorate or iodide while maintaining good chromatographic properties for highly hydrated ions such as chloride, fluoride and sulphate. However, methacrylate polymers are considerably less stable at high pH in the case of anion-exchange polymers or low pH in the

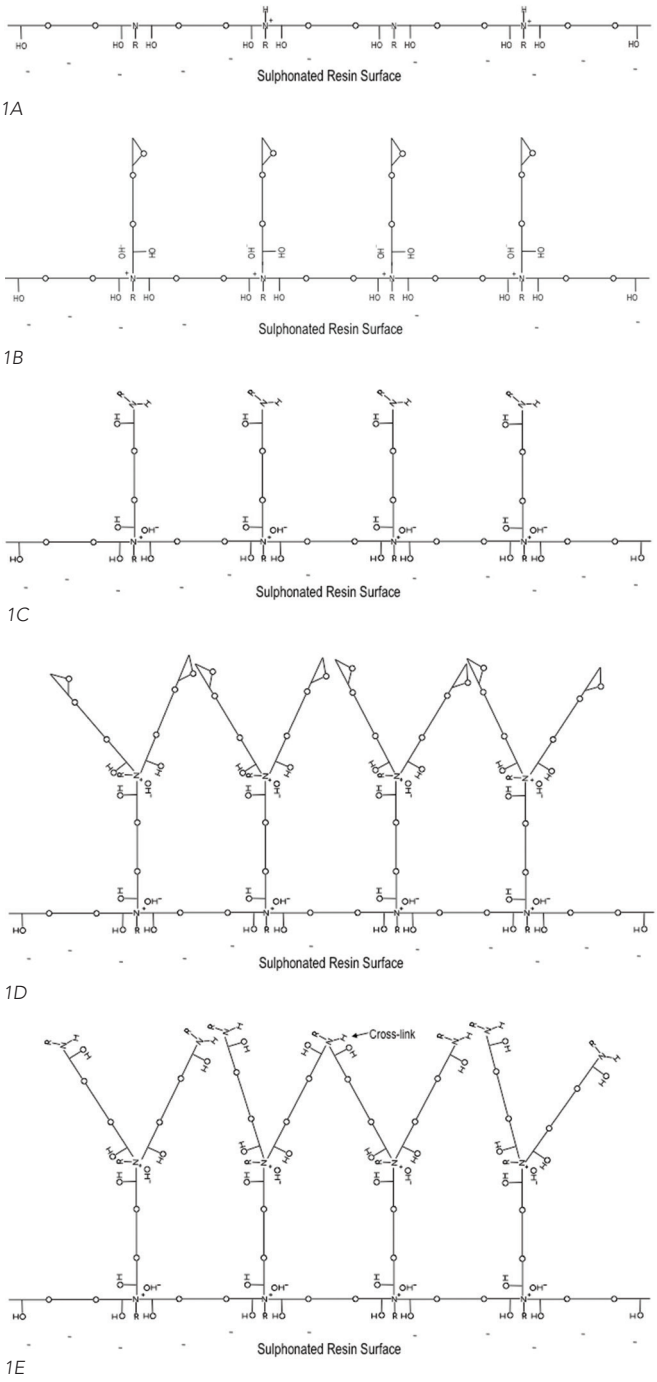

Figure 1

(A) Condensation polymer after deposition of basement condensation polymer. (B) Condensation polymer after deposition of basement condensation polymer and first reaction with diepoxide monomer. (C) Condensation polymer after deposition of basement condensation polymer, first reaction with diepoxide monomer and first reaction with primary amine. (D) Condensation polymer after deposition of basement condensation polymer, first reaction cycle with diepoxide monomer followed by primary amine and second reaction cycle with diepoxide monomer. (E) Condensation polymer after deposition of basement condensation polymer, first reaction cycle with diepoxide monomer followed by primary amine and second reaction cycle with diepoxide monomer followed by primary amine. A possible cross-link site is illustrated.

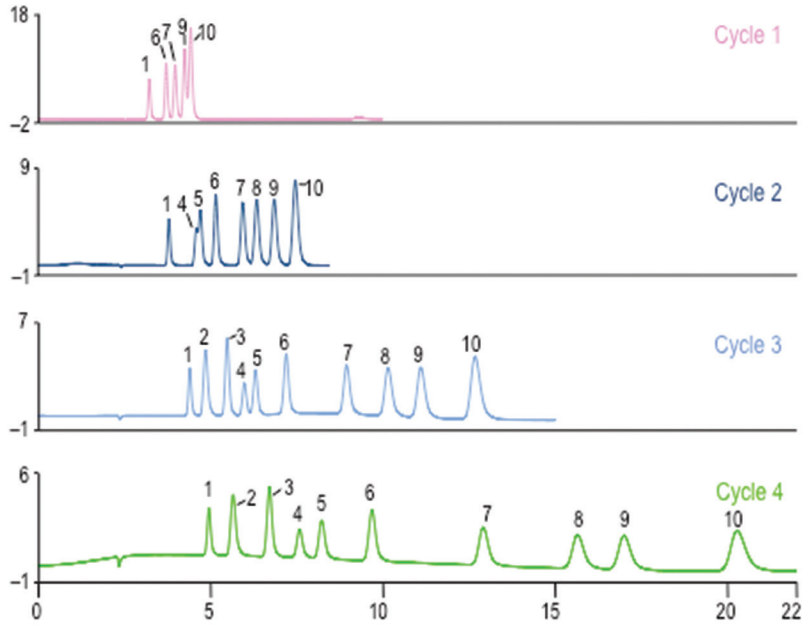

Figure 2

Separation of common organic acids and monovalent inorganic species as a function of reaction cycle number with a BDDGE-methyl amine based hyperbranched condensation polymer. Column dimensions: 4 mm I.D. by 250 mm; eluent: 5 mM KOH; flow rate: 1 mL/min; injection volume: 25 µL; temperature: 30°C; suppressor current: 10 mA; conductivity detection. Peaks: (1) fluoride, 1 mg/L; (2) acetate, 10 mg/L; (3) formate, 5 mg/L; (4) chlorite, 5 mg/L; (5) bromate, 10 mg/L; (6) chloride, 3 mg/L; (7) nitrite, 5 mg/L; (8) chlorate, 10 mg/L; (9) bromide, 10 mg/L; (10) nitrate, 10 mg/L.

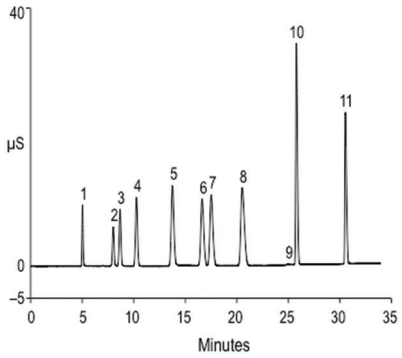

Figure 3

Gradient separation of the common anions and disinfectant by-product anions with the IonPac® AS19 column. Column dimensions: 4 mm I.D. by 250 mm; eluent: 10 mM KOH from 0 to10 min, 10–55 mM from 10 to 25 min; flow rate: 1 mL/min; injection volume: 25 µL; temperature: 30°C; suppressor current: 300 mA; conductivity detection. Peaks: (1) fluoride, 1 mg/L; (2) chlorite, 10 mg/L; (3) bromate, 20 mg/L; (4) chloride, 6 mg/L; (5) nitrite, 15 mg/L; (6) chlorate, 25 mg/L; (7) bromide, 25 mg/L; (8) nitrate, 25 mg/L; (9) carbonate; (10) sulphate, 25 mg/L; (11) phosphate, 30 mg/L.

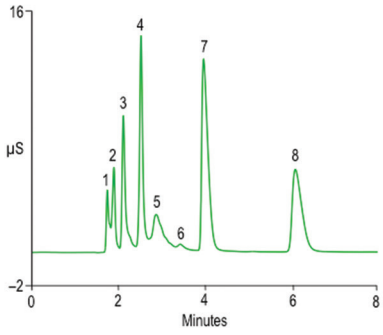

Figure 4

Analysis of phosphate and citrate in a diet cola sample with the IonPac® Fast Anion IIIA column. Column dimensions: 3 mm I.D. by 50 mm guard column with a 3 mm I.D. by 250 mm analysis column; eluent: 22 mM KOH; flow rate: 1 mL/min; injection volume: 1.3 µL; temperature: 30°C; suppressor current: 55 mA; conductivity detection. Peaks: (1) unknown, -- mg/L; (2) unknown, -- mg/L; (3) unknown, -- mg/L; (4) sulphate, 18 mg/L; (5) unknown, -- mg/L; (6) unknown, -- mg/L; (7) phosphate, 224 mg/L; (8) citrate, 174 mg/L.

case of cation-exchange polymers. While methacrylate base polymers are widely used with carbonate eluent systems they are generally incompatible with long-term use with hydroxide-based eluent systems. The hyperbranched condensation polymers described in this article overcome both the hydrophobicity limitations of ion exchange materials based on styrenic monomers and the hydrolytic stability limitations of ion exchange materials based on methacrylate monomers.

Synthesis of the Hyperbranched Anion Exchange Stationary Phase

Hyperbranched anion exchange polymers can be attached to the substrate surface by covalently attaching an epoxy or an amine group to the substrate surface and then subsequently attaching the hyperbranched architecture to the surface groups [7,8]. Alternatively, a polymeric substrate based on styrenic monomers can be surface sulphonated to introduce cation-exchange sites [5,6]. In the latter case, a linear polymer condensation product 'basement layer' is first attached to the cation-exchange sites via electrostatic attraction. Subsequent synthetic steps attached the hyperbranched structure to the basement layer via covalent attachment to tertiary amine groups in the basement layer. The basic synthetic schematic for the synthesis is illustrated in Figure 1A, 1B, 1C, 1D and 1E. Figure 1A illustrates the initial architecture of the stationary phase after attachment of the basement layer. Although the figure illustrates this as a linear strand on the surface of the polymer, the basement layer is undoubtedly a branched structure given the propensity of a primary amine to react with as many as three different epoxy moieties. However, because the basement layer is formed using a 1:1 mole ratio of a diepoxide monomer and a primary amine, the resulting polymer is an uncross-linked water-soluble polymer bound to the surface of the substrate exclusively by electrostatic interaction. Subsequent treatment of the substrate was a large excess of diepoxide monomer (illustrated in Figure 1B) results in virtually all of the tertiary amine groups being converted to quaternary ion exchange sites with a second pendant epoxy group projecting from the surface at each reaction site. Subsequent treatment with a large excess of primary amine (illustrated in Figure 1C) will convert virtually 100% of all the projecting epoxide moieties into secondary amine functionalities. Subsequent treatment of the resulting product for a second time with a diepoxide monomer will result in the attachment of two epoxy monomers attaching to the secondary amine group, producing a quaternary ion exchange site projecting from the surface with two projecting epoxy groups (illustrated in Figure 1D). Subsequent treatment of the resulting product for a second time with primary amine functionality will produce a second generation reaction product with twice as many amine groups projecting from the surface as was present after the first reaction cycle (illustrated in Figure 1E) where a reaction cycle is defined as treatment of the surface with first a large excess of diepoxide monomer followed by a large excess of primary amine monomer. Further illustrated in Figure 1E is the formation of

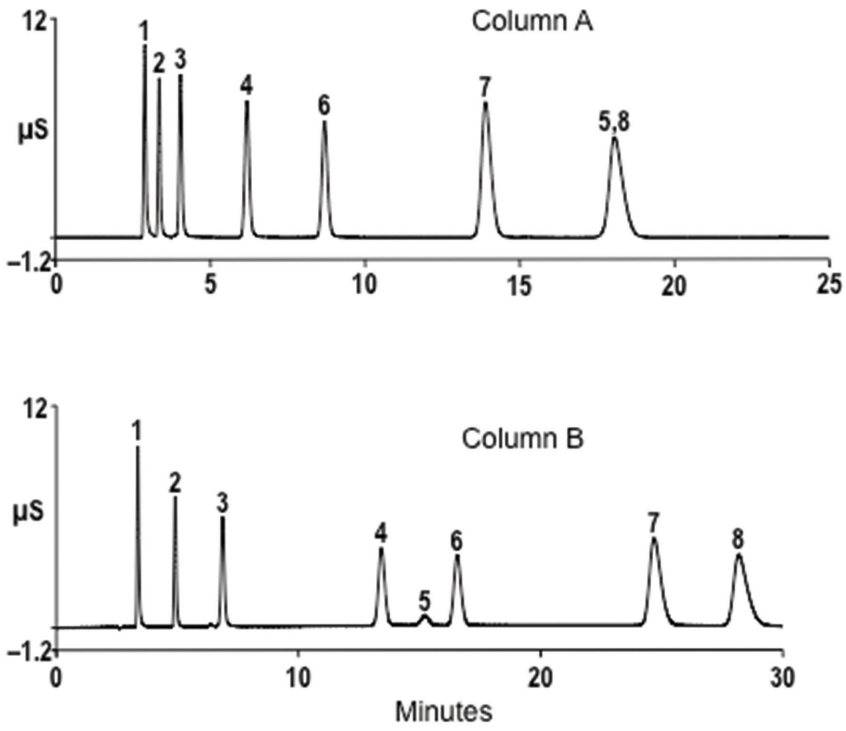

Figure 5

Comparison of the IonPac® AS16 column and the IonPac AS20 column. Column A: IonPac AS16; column B: IonPac AS20; column dimensions: 2 mm I.D. by 250 mm; eluent for column A: 35 mM KOH, eluent for column B: 25 mM KOH; flow rate: 0.25 mL/min; injection volume: 1.25 µL; temperature: 30°C; suppressor current: 50 mA; conductivity detection. Peaks: (1) fluoride, 2 mg/L; (2) chloride, 3 mg/L; (3) sulfate, 5 mg/L; (4) thiosulfate, 10 mg/L; (5) p-chlorobenzenesuphonate, 5 mg/L; (6) iodide, 20 mg/L; (7) thiocyanate, 20 mg/L; (8) perchlorate, 30 mg/L.

a cross-linking site. The probability of the formation of cross-linking sites increases as the number of reaction cycles increase since with each reaction cycle the number of branches doubles. Thus, one would expect the selectivity to be reaction cycle dependent given that cross-links affect water content of the ion exchange polymer and water content of the ion exchange polymer plays a key role in anion exchange selectivity. A secondary aspect of this hyperbranched architecture is that the ion exchange capacity of the hyperbranched structure will increase geometrically as the number of reaction cycles increases, providing a convenient method for manipulating the capacity.

Synthesis of hyperbranched polymers can be accomplished via a number of routes. One attribute of hyperbranched ion exchange polymer synthesis is that the number of reaction steps is rather large compared to other synthetic processes. For example, synthesis of a hyperbranched polymer involving three reaction cycles requires seven separate reactions with seven water rinse cycles between each of the reaction steps. This makes synthesis of hyperbranched polymers rather labour-intensive when using conventional reaction kettle based synthesis methods.

For that reason, we have found that in column synthesis using a conventional ion chromatography pump to deliver reagents in a programmed manner provides a convenient way to automate the many reaction steps. In addition, because the reaction product at the end of each reaction cycle is a chemically stable reaction product is feasible to interrogate the reaction after each reaction cycle to understand the progress of the reaction. Figure 2 demonstrates the utility of in column synthesis while at the same time illustrating the selectivity changes that occur with each reaction cycle. Note that after reaction cycle one the capacity is relatively low and the ability to separate bromide and nitrate is minimal. Figure 4 shows an example of a one reaction cycle phase optimised for fast analysis. After the second reaction cycle, the k' for these ions has roughly doubled while the separation of bromide and nitrate are now baseline resolved and chlorate, bromide and nitrate are nearly equidistant. After the second reaction cycle, bromate and chlorite are well resolved from chloride but nearly completely coelute. Figure 6 shows an example of a two reaction cycle phase optimised for LC-MS of perchlorate. After the third reaction cycle, capacity again has nearly doubled; bromate and chlorite are nearly baseline resolved while the separation of chlorate, bromide and nitrate has shifted substantially so that the gap between bromide and nitrate is much greater than the gap between chlorate and bromide. Figure 5 shows an example of a three reaction cycle phase optimised for the analysis of perchlorate. Finally, after the fourth reaction cycle, capacity has nearly doubled again, bromate and chloride are more than baseline resolved, the resolution of bromide and nitrate has further increased while the gap between chlorate bromide has remained relatively constant compared to reaction cycle three. The shifts in selectivity and changes in capacity with each reaction cycle clearly demonstrate the predicted geometric increase in capacity with each reaction cycle and provide evidence that cross-link of the hyperbranched film is increasing with each reaction cycle. The fact that these changes in selectivity can be studied in the course of the reaction further demonstrates the utility of in column synthesis.

As one can readily imagine from seeing these shifts in selectivity and capacity, optimising the reaction conditions and the number of reaction cycles as well as the epoxy and amine reagents allow for the development of ion exchange materials specifically optimised for target applications. Figure 3 illustrates the selectivity of a column developed specifically for the analysis of bromate in environmental samples when using a hydroxide-based eluent system. In this case, the column utilises three reaction cycles but the final reaction involves use of a tertiary amine rather than a primary amine such that all of the ion exchange sites are in a quaternary form.

When analysing production of syrup used in the preparation of carbonated beverages, it is important to measure the phosphate concentration in order to assess whether or not the bottling plant is using the correct dilution factor for the syrup. Given the production rate of such a manufacturing facility it's important that the analysis of phosphate in the syrup is rapid in order to achieve the necessary analytical throughput. Figure 4 illustrates the selectivity of a column specifically optimised for the analysis of phosphate and citrate. As with the previous case, the final reaction step involves treatment of the pendant epoxy groups with a tertiary amine in order to provide quaternized ion exchange sites throughout the ion exchange polymer. Because the selectivity is excellent after one reaction cycle, further reaction cycles are unnecessary for this application. At the same time the

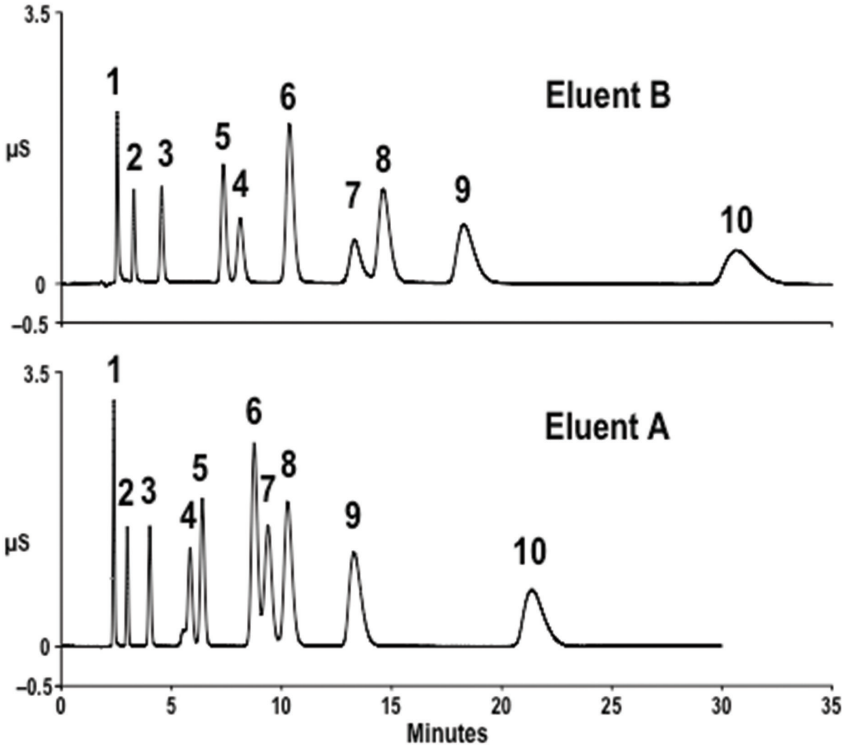

Figure 6

Separation of environmental anions with a volatile eluent with the IonPac® AS21 column. Column dimensions: 2 mm I.D. by 250 mm; eluent A: 12.5 mM KOH, eluent B: 200 mM methyl amine; flow rate: 0.35 mL/min; injection volume: 2.5 µL; temperature: 30°C; suppressor current: 50 mA; conductivity detection. Peaks: (1) fluoride, 2 mg/L; (2) chloride, 2 mg/L; (3) nitrate, 5 mg/L; (4) sulphate, 5 mg/L; (5) iodide, 20 mg/L; (6) perchlorate, 30 mg/L; (7) chromate, 30 mg/L; (8) tungstate, 30 mg/L; (9) phosphate, 30 mg/L; (10) arsenate, 30 mg/L.

low capacity of the column facilitates rapid analysis of phosphate and citrate.

When analysing environmental samples for perchlorate contamination, it is critical to be able to confirm that the perchlorate identified in the chromatogram is perchlorate and not another coeluting contaminant. For that reason, EPA method 314.1 specifies analysis using the IonPac AS16 column shown in the upper chromatogram of figure 5. As shown, p-chlorobenzenesulphonate coelutes with perchlorate on the AS16 while the retention time for p-chlorobenzenesulphonate is half that of perchlorate on the IonPac AS20 (shown in the lower chromatogram of Figure 5). Clearly the selectivity of these two columns is quite different and the combination of these two selectivities provides added confidence in the analysis of perchlorate in environmental samples, especially in the case of samples that may be compromised by a number of other environmental contaminants. Synthesis of the hyperbranched polymer used in preparation of the IonPac AS20 utilises three reaction cycles with a primary amine used in all three reaction cycles. Thus, in the case of the AS20 the outermost structure of the hyperbranched polymer is decorated with secondary amine groups that further modify the ion exchange selectivity of the hyperbranched polymer.

Another option in the analysis of perchlorate is IC-MS. Figure 6 illustrates the chromatographic properties of a stationary phase optimised for IC-MS. The polymer architecture utilises 2 reaction cycles with primary amine reagent used in all reaction cycles so that the outermost ends of the hyperbranched polymer are weak base ion exchange sites. In this case, the polymer was optimised to minimise perchlorate retention so that the column can be used with either potassium hydroxide as illustrated in the lower chromatogram or a methylamine based mobile phase which allows operation without a suppressor (illustrated in the upper chromatogram). In either case, perchlorate can be analysed in under 10 minutes with excellent resolution of perchlorate from sulphate which might otherwise compromise analysis of perchlorate.

Conclusion

Synthesis of hyperbranched polymers provide a wide variety of anion exchange selectivities based on the reaction conditions, reagents and the number of reaction cycles. The utility of specific architectures for the analysis of bromate in drinking water, the analysis of perchlorate in environmental samples and the analysis of phosphate in carbonated beverage syrups has been demonstrated. A large number of alternative architectures are possible through the manipulation of the reagents involved in the synthesis, providing the opportunity to develop optimised ion exchange selectivities for a wide variety of other specific applications.

References

[1] H. Small, T. S. Stevens, W. C. Bauman, Anal. Chem. 47 (1975) 1801.

[2] H. Small, Ion Chromatography, Plenum, New York, 1989.

[3] P. R. Haddad, P. E. Jackson, Ion Chromatography Principles and Applications (Journal of Chromatography Library, Vol. 46) Elsevier, Amsterdam, 1990.

[4] J. S. Fritz, D. T. Gjerde, Ion Chromatography, Wiley-VCH, Weinheim, 2000.

[5] C. Pohl, C. Saini, US Pat. 7 291 395 (2007)

[6] P. Kuban, P. K. Dasgupta, C. A. Pohl, Anal. Chem. 79 (2007) 5462.

[7] B. Buszewski, M. Jackowska, S. Bocian, P. Kosobucki, B. Gawdzik, J. Sep. Sci. 34 (2011) 601.

[8] Y. Li, J. Yang, J. Jin, X. Sun, L. Wang, J. Chen, J. Chrom. A. 1337 (2014) 133