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Adsorption of small uremic toxin molecules on MFI type zeolites from aqueous solution

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Abstract Adsorption properties of zeolites were investigated for the removal of *p*-cresol from aqueous solutions at 37 °C within the context of studying alternative methods to dialysis for removing uremic toxin from blood. MFI-framework type zeolites with different degrees of hydrophobicity and charge compensating cations were prepared: one pure silica MFI and four alumino-silicate MFIs (Si/Al = 30), with H^+, Na^+, K^+ and Mg^{2+} as charge compensating cations. Adsorption isotherms and microcalorimetric measurements show a high affinity of *p*-cresol for all MFI type zeolites. The best capacity is obtained for the pure silica MFI, whereas the alumino-silicate samples show a higher affinity in the low concentration range. In the case of pure silica sample, the microscopic adsorption mechanism including the role of confined water is elucidated with the help of NMR, X-ray analysis (including Rietveld refinement) and Monte Carlo simulations. For all samples the high affinity is preserved in physiological serum solution, even in the presence of other toxin molecules such as urea. It is also shown that the compensating cation state of the samples is imposed by the physiological medium.

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1 Introduction

Uremia is a syndrome where the human kidney system becomes unable to purify blood from metabolism products. In the final state of the illness the blood of the patient has to be purified by a dialysis system based on polymer membranes in regular intervals (sessions of four hours). Generally, uremic toxins can be subdivided in three groups (Vanholder et al. 2003): "classical" free solute molecules such as urea are small and are efficiently removed by dialysis. The second group contains middle size molecules that have a molecular weight superior to 500 $g \cdot mol^{-1}$. The third group consists of toxin molecules like *p*-cresol. They are normally bound to proteins by van der Waals forces but in the case of uremia, a certain fraction is free. It is essentially this third group of toxins which is insufficiently eliminated by dialysis procedures (only 29% in contrast to small free soluble molecules such as urea and creatinine which are eliminated with removal rates of 75% and 69%, respectively (Lesaffer et al. 2000)). The remaining molecules might cause a progressive intoxication of the patient that may lead to death (Dou et al. 2002).

An alternative way of blood purification could be by adsorption onto inorganic microporous materials such as zeolites. They are supposed to be non-toxic, unaffected by degradation under physiological conditions, have channel systems corresponding to the dimensions of small uremic toxin molecules and show selective adsorption with adsorption capacities potentially high. In a first screening study, a set of uremic toxins, including urea and *p*-cresol, were tested for adsorption from aqueous solutions by zeolites of

different framework types (Wernert et al. 2006). MFI type zeolites were found to adsorb efficiently *p*-cresol (Wernert et al. 2005), therefore, this zeolite framework type has been selected for further studies presented here.

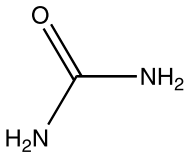
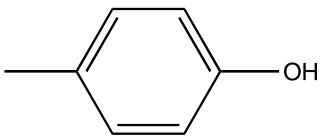
Free p-cresol concentration in blood of healthy persons is relatively low, around 6 µM, but reaches up to 200 µM in case of renal failure (Vanholder et al. 2003). The toxin is produced by the degradation of amino acids due to intestinal bacteria.

The aim of this study is to show how adsorption of a specific molecule such as *p*-cresol is influenced by the modification of the physical and chemical properties of the zeolite but also by the composition of the liquid phase, a simple saline buffer solution without any further organic molecules.

2 Materials, experimental methods and modeling

Toxins studied are p-cresol and urea with purity of 99% and 99.5% purchased from Aldrich and Prolabo respectively. The physical-chemical properties of uremic toxins studied are presented in Table 1. *p*-Cresol is a phenolic compound containing a methyl group on para position, the size of urea and p-cresol is close to that of the zeolite channels. The zeolite framework type used was high silica zeolite MFI. It's channel system is composed of a straight channel in the crystallographic *b* direction interconnected to a second zig-zag channel in the crystallographic *a* direction (Van Bekkum et al. 2001). Pores are constituted of rings of 10 oxygens (Meier et al. 1996) (Fig. 1). The adsorbents used are silicalite (pure silica MFI) with about a particle size around 18 µm and ZSM-5 (alumino-silica) with a

Table 1 Physical and chemical properties of urea and p-cresol. Chemical formula, skeletal formula, molecular weight, pKa, normal concentration, uremic concentration and size of two uremic toxins urea and p-cresol are presented. The size provided from an estimation done with Cerius^2 in ellipsoid model

Molecule	Structure	MW ($g \cdot mol^{-1}$)	pKa (298 K)	Cn (µM)	Cu (µM)	Size (nm) x y z
Urea $CO(NH_2)_2$		60	0.1	< 6700	> 38000 ±18000	0.56 0.6 0.30
p-Cresol $CH_3C_6H_4OH$		108	10.3	6	> 186 ±40	0.66 0.76 0.39

MW: molecular weight; Cn: normal concentration; Cu: uremic concentration. Size estimated from Cerius^2 with ellipsoid model

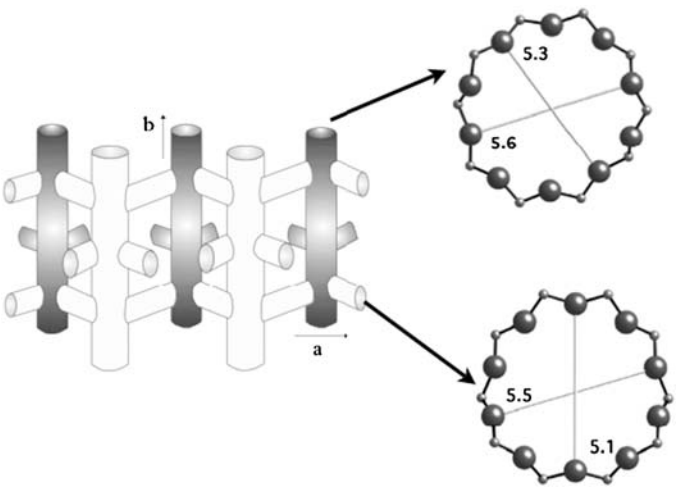


Fig. 1 Representation of MFI structure showing the interconnections and the dimensions of the two different channel systems

Table 2 Characteristics of MFIs employed. The two different Si/Al ratios are presented. For Si/Al ratio of 30.4, the different charge compensating cations are given

Zeolite	Cations	Si/Al ratio
ZSM-5	H^+	30.4
	K^+	
	Na^+	
	Mg^{2+}	
Silicalite	–	∞

particle size around 20 µm. Silicalite was prepared by a procedure reported in literature (Robson and Lillerud 2001) using 72 g H_2O, 2.26 g tetrapropylammonium, 0.296 g NH_4F and 12 g silica. The clear gel was heated under autogenous water pressure in a Teflon lined autoclave at 200 °C for 15 days. The silicalite obtained was washed with deionised water, dried and calcinated in oxygen atmosphere at 520 °C for 6 h in a furnace using a heating rate of 0.2 °C·min^{-1}.

The Al-containing H-MFI parent zeolite with a Si/Al ratio of 30.4, subsequently used for ion exchange was synthesized by the Laboratoire de Matériaux à Porosité Contrôlée (LMPC) Universite de Haute Alsace (Guth et al. 1992). The sample was calcinated at 520 °C for 6 h under the same conditions as above to remove the template.

Na-MFI, K-MFI and Mg-MFI were prepared by cation exchange. In that aim, H-MFI was treated at 80 °C during 48 h in 1 M solutions of NaCl, KCl,or $MgCl_2$ with draining after 24 h (Table 2). The solution/zeolite mass ratio was 120.

For adsorption measurements, sodium chloride solution (purchased from Prolabo with a purity of 99.5%) was used at concentration of 9 g·L^{-1}. Dulbecco Phosphate Buffer Saline (DPBS) physiological solution was purchased from Invitrogen and contains: NaCl (8 g·L^{-1}), $CaCl_2$ (0.1 g·L^{-1}), $MgCl_2$ (0.1 g·L^{-1}) KCl (0.2 g·L^{-1}), KH_2PO_4 (0.2 g·L^{-1}) and NaH_2PO_4 (2.16 g·L^{-1}).

Subsequent ionic re-exchanges were performed by exposing the cation containing MFIs to DPBS solution during 12 hours at 37 °C under stirring. The zeolites were finally washed with deionised water and dried.

2.1 Adsorption experiments

Adsorption from solution experiments were carried out by the solution depletion method (Lyklema 1995) in stoppered tubes. Stirring was provided for 12 hours at 37 °C (kinetic investigations showed that this time is sufficient to reach equilibrium). Liquid and solid phase were then separated by centrifugation. Adsorption experiments were performed either from pure water, physiological solution ([NaCl]: 9 g/L or DPBS, respectively), and from a physiological solution containing urea (38 mM). The concentration of p-cresol in supernatants was measured thanks to a HPLC set-up (Agilent 1200 series) with diode-array detector and Agilent Zorbax SB-C18 column. Calibration was done using an external standard in order to increase precision of p-cresol concentration and separate p-cresol of other compounds like urea.

Adsorption enthalpies were measured by the microcalorimetric method in aqueous solution. The calorimetric experiments were carried out in a Tian-Calvet microcalorimeter following a titration procedure. The adsorption takes place by adding a p-cresol solution step by step inside the cell were the zeolite is maintained in suspension by stirring. In this study, 50 mg of zeolite were used and the p-cresol concentration was chosen based on the adsorption isotherm data. The microcalorimetric studies of p-cresol were performed at 37 °C in aqueous solution. More details about the calorimeter used in this study are given in Ref. (Denoyel 2002). Integral enthalpies of adsorption are presented in this work.

2.2 Characterization methods

The zeolites obtained were characterized by powder XRD for phase purity (Bragg Brentano geometry, Siemens D5000) using Cu Kα radiation. SEM/EDX was performed for morphological and chemical composition information (Cambridge S90B with EDAX DX4 SUTV detector). Semi-quantitative EDX analysis was performed at each step of ion exchange.

Specific surface areas were determined by nitrogen adsorption at 77 K with a Micrometrics ASAP 2010 apparatus. Before adsorption samples were outgassed during 12 hours at 150 °C at a pressure lower than 10^{-2} mbar. Thermogravimetric analysis were performed with a TGA Q 500 apparatus from TA Instruments with a heating ramp of 5 °C·min^{-1} under synthetic air flow.

2.3 Spectroscopy

Solid state NMR spectra were obtained on a Bruker DSX 400 NMR operating at 9.4 T, which corresponds to a Larmor frequency of 104.3 MHz, 100.7 MHz, and 400.4 MHz for ^{13}C and ^{1}H, respectively. Approximately 50 mg of samples were introduced in a 4 mm zirconia rotor and spun between 5 and 10 kHz in a doubly tuned Bruker probe. ^{13}C were observed with cross polarization (CP) from the neighbouring ^{1}H nuclei. ^{13}C CPMAS parameters were: 90° pulse length of 3.2 µs, a contact time of 3 ms and a recycle delay of 3 s, and 4096 to 10240 scans were accumulated. The ^{27}Al and ^{13}C NMR spectra were performed at room temperature and external references were used for each case, that is, aqueous $Al(H_2O)_6^{3+}$ and TMS, respectively.

2.4 X-ray diffraction

The powder X-ray diffraction data of MFI-p-cresol were collected on a PANalytical MPD X'Pert Pro diffractometer in a Debye-Scherrer geometry equipped with a capillary sample holder, a hybrid mirror monochromator (CuKα_1 radiation, $\lambda = 1.5406$ Å) which gives the monochromatic parallel beam geometry and a X'Celerator Real-Time Multiple Strip detector (active length = 2.12°(2θ)). The incident beam configuration was: a ceramic Cu-LFF tube (45 kV, 35 mA), fixed divergence slit (1/16°), hybrid monochromator, anti-scatter slit (1°). The diffracted beam with the X'Celerator configuration had an anti-scatter shield and a Soller slit (0.02 rad). Powder MFI-p-cresol was introduced in a Mark-tube made of special glass (no. 14, outside diameter 0.3 mm, Hilgenberg Gmbh) then the capillary tube was mounted on a precise goniometric head which is screwed on a rotary sample stage, the spinning rate was 1 rotation per second. The powder patterns were collected at 295 K in the range $6 < °(2\theta) < 85$, step = 0.008°(2θ), time/step = 2970 s). The resulting PXRD patterns of MFI-p-cresol were indexed with orthorhombic unit cell parameters in space group $P2_12_12_1$ (no. 19).

2.5 Theoretical approach

In order to understand the process of adsorption from a microscopic point of view Monte Carlo simulations were carried out using the grand-canonical (μVT) ensemble (Metropolis et al. 1953). No bias algorithms were used. For the simulations presented in this work, the temperature was fixed at 310 K (37 °C) and the volume is defined by two unit cells of silicalite ($[Si_{96}O_{192}]_2$) with cell parameters a = 20.022 Å, b = 19.899 Å, 2c = 26.766 Å and $\alpha = \beta = \gamma = 90°$. The chemical potential corresponds to a reservoir of adsorbate molecules (*p*-cresol), being in equilibrium with the adsorbed system. There are no water molecules in the simulated system. The grand-canonical simulation tends to equalize the chemical potentials of both the reservoir of molecules and the adsorbed phase by creating (deleting, respectively) adsorbates into (from) the zeolite, therefore mimicking an adsorption-desorption equilibrium process. When the chemical potentials are equal the thermodynamic equilibrium is reached. The Cerius^2 packages (Cerius 2003) with the burchart 1.01-DREIDING2.21 forcefield (Mayo et al. 1990; de Vos Burchart 1992) were used and periodic boundary conditions were applied to compute the Ewald sum for electrostatic interactions. Each set of simulation was run for 60 millions of iterations to ascertain that equilibrium was reached. VMD (Humphrey et al. 1996) software was used for graphics.

3 Results and discussion

3.1 Basic characterization

SEM images (Fig. 2a,b), together with EDX analysis and powder XRD confirmed that zeolites of MFI framework type were present. Figure 1 shows the principal channel system arrangement and channel dimensions in Angstroms. The values of equivalent specific surface areas and pore volume (360 $m^2\,g^{-1}$ and 0.17 $cm^3\,g^{-1}$ for silicalite, and around 240 $m^2\,g^{-1}$ and 0.11 $cm^3\,g^{-1}$ for the other samples) determined by nitrogen adsorption correspond to literature values (Llewellyn et al. 1993).

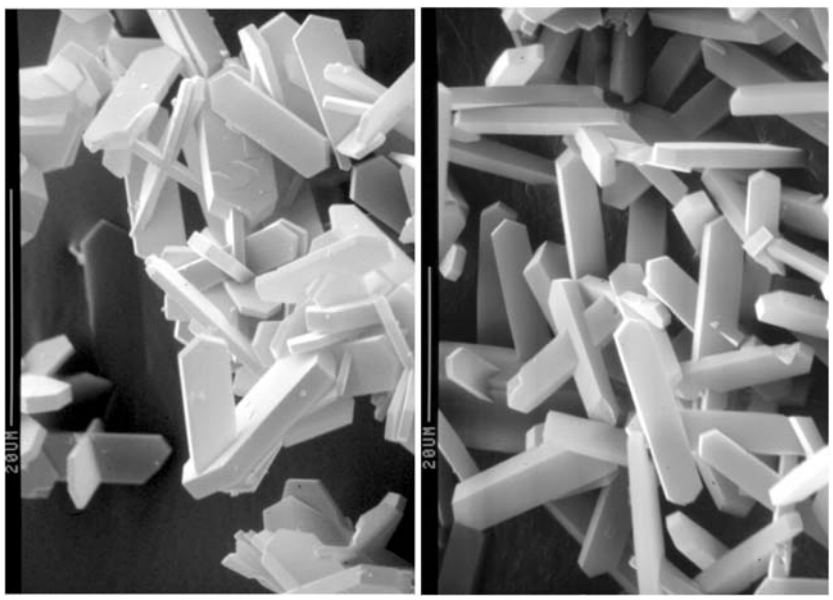


Fig. 2 Morphologies of the two different MFI-zeolites employed. (**A**), *left*, silicalite (pure silica MFI). (**B**), *right*: ZSM-5 (Si/Al = 30.4)

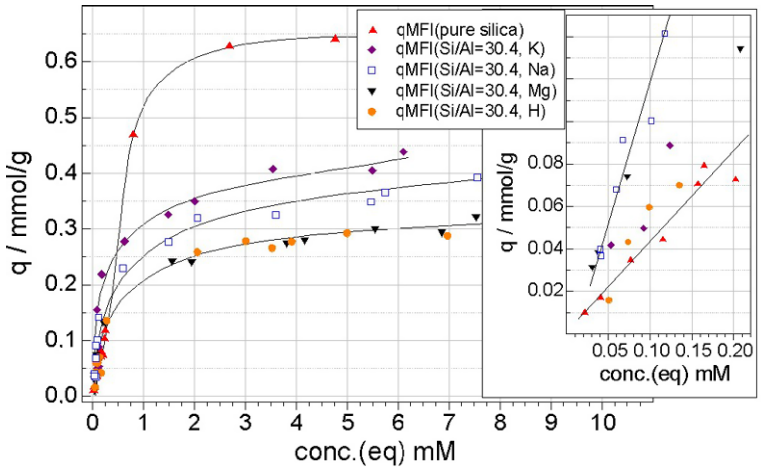


Fig. 3 Adsorption isotherms in water of p-cresol onto MFI type zeolites (Si/Al equal to ∞ and 30.4—with different charge compensating cations H, Na, K and Mg), performed in aqueous solution at 37 °C during 12 hours. The *insert at right* is a zoom in uremic concentration range

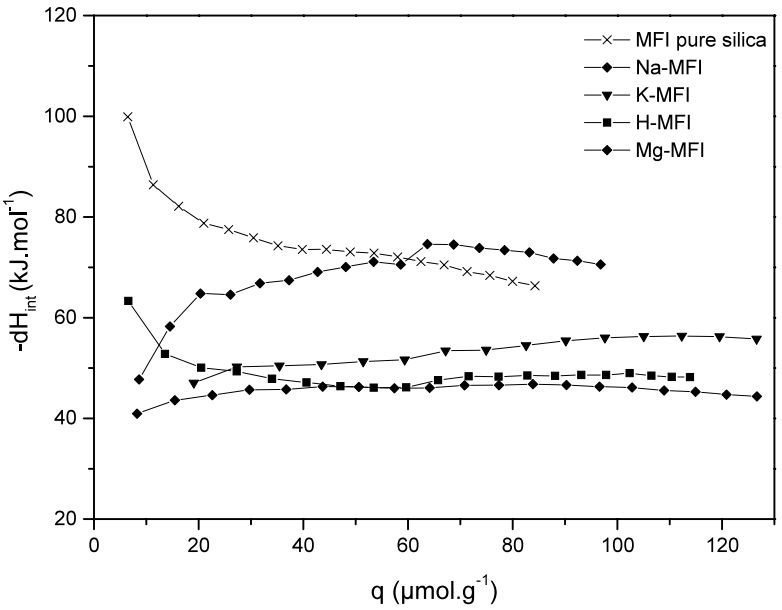


Fig. 4 Microcalorimetric measurements-adsorption enthalpies as a function of adsorbed amount is presented for each MFI. Experiments were performed in aqueous solution at 37 °C

3.2 Thermodynamic analysis of adsorption from solution

The shape of adsorption from solution isotherms suggests a progressive saturation of solid (Fig. 3). Initially a constant slope is followed by a plateau. Shapes obtained correspond to Langmuir type (Limousin et al. 2007) (L-type). The high value of initial slope shows a high affinity between p-cresol and MFIs. The highest adsorption capacity is obtained for silicalite (about 0.65 mmol/g, which corresponds to 3.66 p-cresol molecules per unit cell) and decrease in the following order K-MFI, Na-MFI, Mg-MFI and H-MFI (Fig. 3). In the uremic concentration range (185 µM), the adsorbed amount is far from saturation: only a fraction of the adsorptive sites is occupied. Silicalite sample presents an adsorption capacity superior than other samples, but the affinity is superior for alumino-silica MFIs as shown by the initial slope in the insert of Fig. 3. Complementary NMR measurements exhibited that all Al was in tetrahedral position, in other words no extra framework Al was present. The influence of charge compensating cations on adsorption has been further studied by using microcalorimetric method. The integral adsorption enthalpies of p-cresol onto MFIs at 37 °C from aqueous solution are shown in Fig. 4. Three trends are evidenced. First, the highest adsorption enthalpy, notably at low coverage or filling, is obtained for silicalite sample. Second, adsorption enthalpies variations are relatively constant and similar for monovalent charge compensating cations: this means the distribution of different energetic sites is rather homogeneous. Third, Mg-MFI sample gives a high and increasing adsorption enthalpy followed by a plateau. The respective positions of both adsorption isotherms and adsorption enthalpy curves is probably related to the adsorption mechanism at the microscopic level that may be different between pure silica sample and cationic exchanged ones. Silicalite

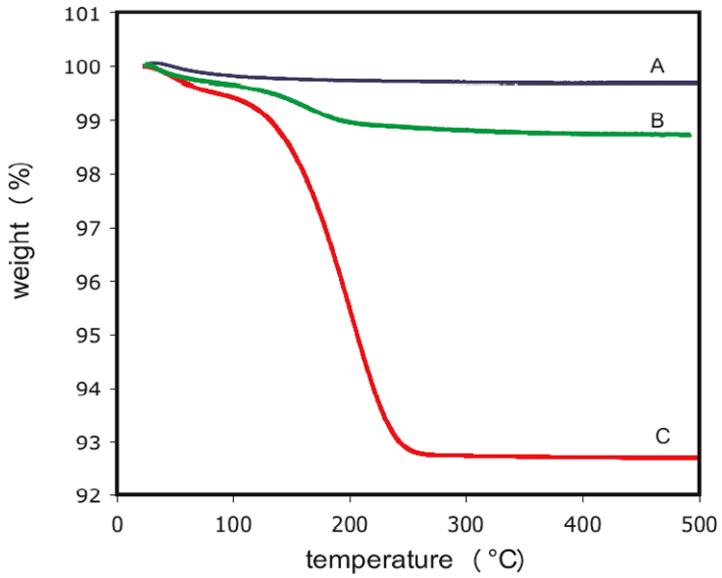


Fig. 5 Thermogravimetric measurements on silicalite. The mass loss in function of temperature is presented. The heat ramp was 5 K·min^{-1}

is indeed known to be hydrophobic as shown for example by Eroshenko et al. (2001) who evidenced that a pressure as high as 100 MPa may be needed to fill silicalite with water. As a consequence, in conditions of adsorption from solution experiments, the pure silica sample is not initially filled with water. When p-cresol is added, it can be adsorbed by the silicalite without having to displace water molecules from the channels. At the opposite, cationic exchanged zeolite are hydrophilic and are filled spontaneously by water: adsorption of p-cresol needs the displacement of some water molecules. This difference between the two types of sample may explain the higher enthalpy of adsorption in the case of silicalite. The strong and increased adsorption enthalpy in the Mg-MFI sample is probably caused by p-cresol interaction with the strong electric field provided by the divalent cation. Despite this higher enthalpy of adsorption on silicalite, a highest slope at the origin is obtained for the cationic samples, which means that the Gibbs energy of adsorption is more negative for cationic samples. This shows that the entropy variation during the adsorption process is higher in the case of silicalite. This is typical of phenomena that involve hydrophobic interaction. In the present case a possibility is that the p-cresol adsorption modifies the wettability of silicalite due to the introduction of polar functions inside the channels. These water molecules introduced in the pores thanks to p-cresol may loose a large number of freedom degree as compared with the bulk situation, leading to this large entropic effect. Such interpretation is in agreement with TG results (Fig. 5). Sample A is silicalite contacted with pure water, samples B and C contain 48 µmol·g^{-1} and 600 µmol·g^{-1} of p-cresol, respectively. Two steps are visible on the curves. The first one below 150 °C corresponds to water desorption. The second one, around 200 °C, corresponds to p-cresol removal. The evolution of the first step with p-cresol content shows the influence of its adsorption on silicalite filling by water.

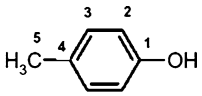
To finish with this comparison between the samples adsorption isotherms, the highest capacity observed for silicalite is simply due to the highest accessible pore volume which is reduced when cations are introduced in the network.

3.3 Microstructural analysis in the case of silicalite

In order to investigate the interaction of p-cresol and zeolite from a structural point of view at high adsorption content, Magic Angle Spinning NMR of ^{13}C was performed on silicalite. The results are given in Table 3. MAS NMR of ^{13}C was performed on p-cresol in bulk and in silicalite for comparison. The values of chemical shift change from bulk phase to adsorbed phase, especially in the cases of carbon 1 (hydroxyl function) and carbon 5 (methyl group), this change of chemical shift can indicate that these two functions are the most influenced the by interaction of the molecule with zeolite walls.

Rietveld refinement of X-ray diffraction data gave further insight on the adsorbate-zeolite interaction. From Rietveld refinement, the reliability factors were Rp = 3.43%, wRp = 4.29% and $\chi^2 = 0.756$ for MFI-p-cresol. Further details on the Rietveld refinement and crystallographic data will be presented in a further publication. To resume, about 3.2 p-cresol molecules per unit cell of MFI-p-cresol are located on one crystallographic site inside the straight channel at the intersection of the straight and zigzag channels (Figs. 6 and 7). About the same amount of water molecules are situated on one crystallographic site inside the zig-zag channel (Fig. 6). The shortest Ow1 to framework oxygen distance being 3.27(7) Å, the structural study reflects the hydrophobic character of the pure silica framework.

Table 3 Chemical shift values of Magic Angle Spinning NMR of ^{13}C of p-cresol in bulk and adsorbed onto zeolite MFI. Values of chemical shift are presented for each carbon in bulk and in silicalite as well as the medium shifts

	Carbon	p-Cresol bulk	p-Cresol in silicalite	Δ shift
 p-crésol	C1	152.8	154.0	+1.2
	C2	115.4	114.5	−0.9
	C3	130.3	129.2	−1.1
	C4	130.3	129.2	−1.1
	C5	19.9	18.3	−1.6

Chemical shifts in ppm from TMS

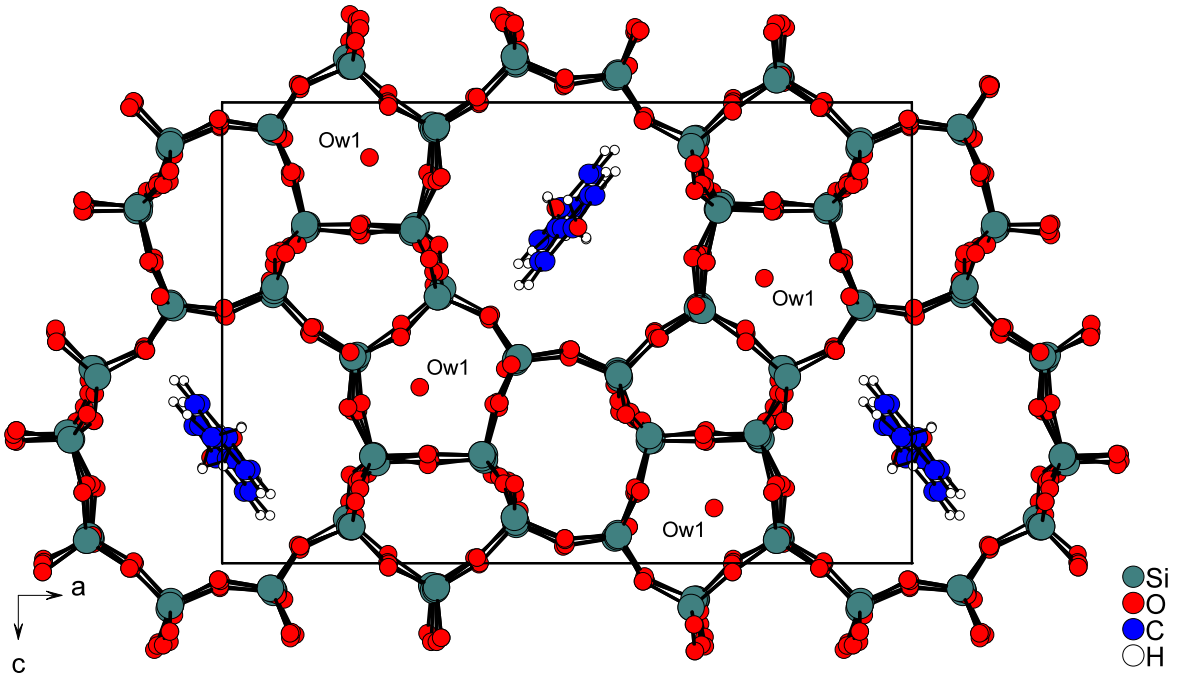


Fig. 6 Projection along [010] of silicalite-p-cresol structure. p-Cresol is present in the straight channels (b-direction) at the channel intersections while water molecules represented by oxygen (*Ow1*) are in the middle of the zigzag system

Microstructural aspects may also be highlighted by Monte Carlo simulations. Figures 8a and 8b depict the very last p-cresol/MFI structure obtained at saturation in the pure silica zeolite. Two types of adsorption sites can be seen. First, located in the straight channels (ball molecule, (Fig. 8a)) and second, located in the zigzag channels (stick molecule (Fig. 8a)). When all the sites are occupied the amount of molecules adsorbed in the zeolite is 1.034 mmol/g (twelve p-cresol molecules per two unit cells of zeolite) whereas only 0.65 mmol/g of p-cresol was found from experiments. Therefore, not all sites are occupied and this can be explained as follows, using the energy arguments. From the Monte Carlo simulations the mean energy per p-cresol molecules amounts to -77 ± 15 kJ mol^{-1}, which is in reasonable agreement with calorimetric measurements (see Fig. 4, -65 kJ mol^{-1}). In fact, there are three energetically different types of adsorption sites. The most stable ones correspond to the range of energies between -104 and -92 kJ mol^{-1}, the second type has energies between -92 and -71 kJ mol^{-1} and the least stable one is in the range -71 to -41 kJ mol^{-1}. The detailed analysis of the various sites shows that, the two most stable sites correspond to positions in the straight channels (Fig. 8a). The difference originates from the rotation of the p-cresol molecule within the channel. In the third type of sites, some positions are located in the straight channel (the most unfavorable) and

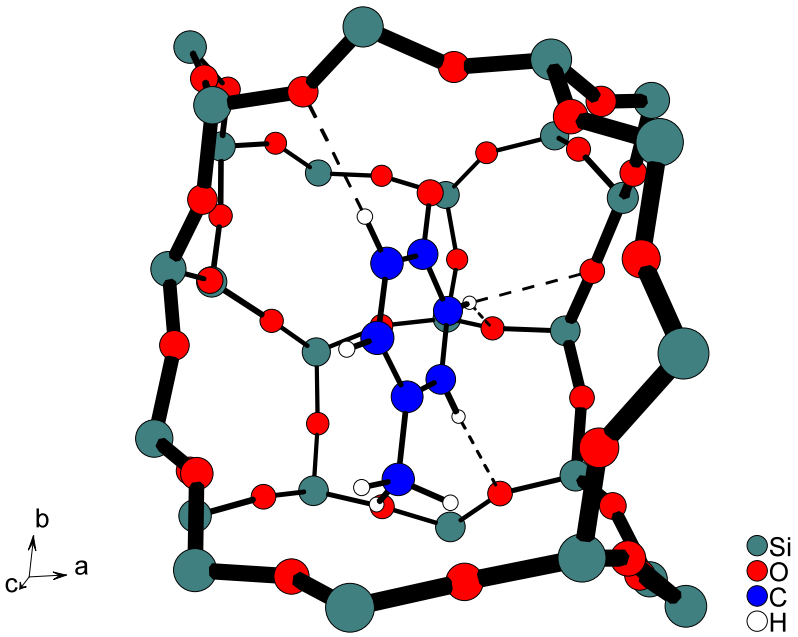


Fig. 7 View of the straight and zigzag channels intersection perpendicular to the straight channel of silicalite-p-cresol. The hydrogen bonding scheme (1.8 Å < O···H < 2.6 Å) is plotted as *dashed bonds*, indicating the proximity of the hydrophobic part of the molecule to the channel wall. The 10-MRs opening of the zigzag channels are alighted for clarity

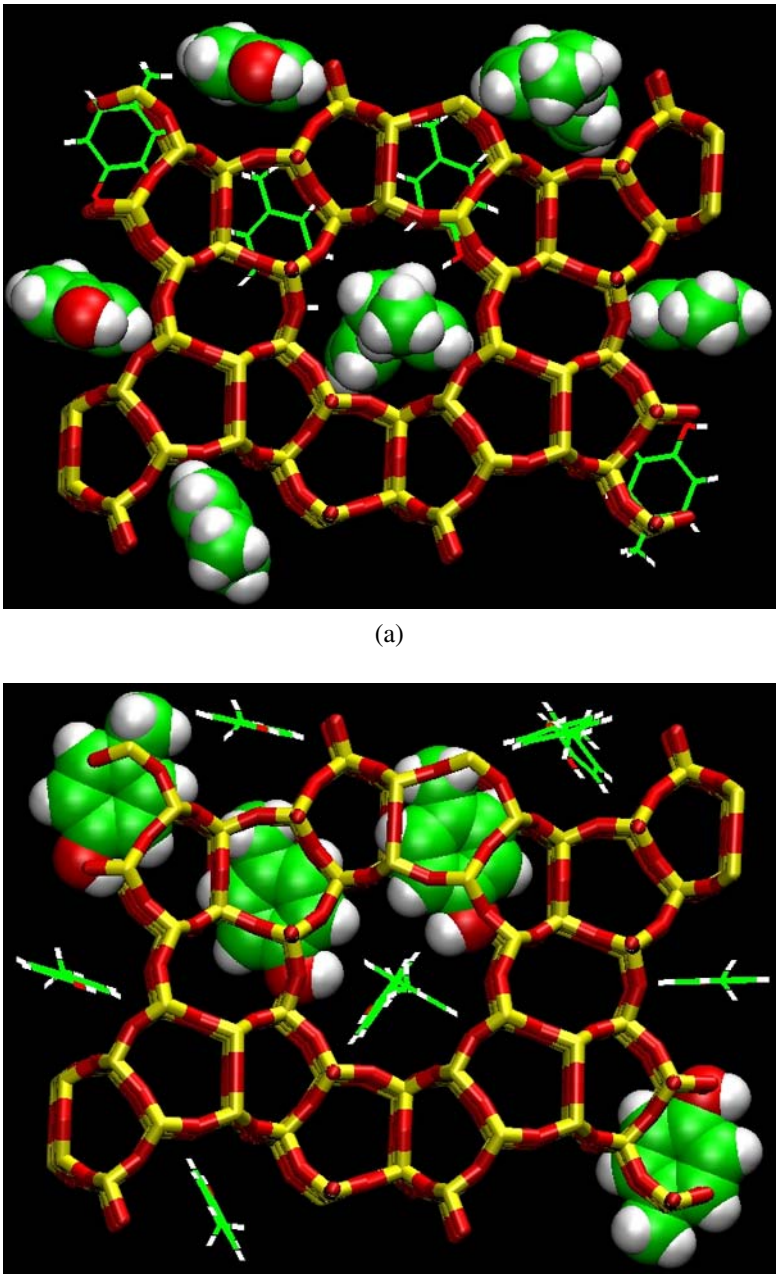
the others, more stable, are located in the zigzag channels. As we have mentioned above, there are four molecules of this type (that is located in the zigzag channel) per two unit cells of zeolite. However, from the Rietveld refinement of the XRD diagram the zigzag channel sites were not found to be occupied by p-cresol: although these sites could stabilize p-cresol molecule, they are already occupied by co-adsorbed water molecules (Ow1, see Fig. 5). Future simulations of adsorption have to take this co-adsorption phenomenon into account. As a consequence, only eight molecules out of twelve are present per two unit cells of zeolite, and the amounts of adsorbates equals 0.7 mmol/g, which roughly corresponds to the experimental findings (0.65 mmol/g).

3.4 Adsorption from physiological solutions

The results of adsorption in aqueous solution can be seen in Fig. 3. Adsorptions from physiological solution (saline solution ([NaCl]: 9 g/L or saline buffer solution (DPBS) without further organic molecules such as amino-acids, peptides, sugars, lipids and proteins) at 37 °C were performed in order to approach a practical system. Discrete points on the isotherms comparing adsorption from pure water and from saline solution (NaCl 9 $g{\cdot}L^{-1}$) are presented in Fig. 9. A change of isotherm's slope from aqueous solution to physiological solution on ZSM-5s (H^+, Na^+, K^+ and Mg^{2+} as charge compensating cations) could be observed. This shift was higher in the case of H-MFI and Mg-MFI. The slope of isotherms depends on the affinity between p-cresol and MFIs: a higher slope means a higher affinity. As can be seen, silicalite (pure silica MFI and, therefore, without charge compensating cations) is not concerned by this change of affinity. This behavior lets think about an ionic exchange effect. In fact, it was found that during these experiments two different phenomena take place at the same time, adsorption and ion exchange: Adsorption behavior tends towards a unique value—that of a Na exchanged sample, whatever the initial cationic state (H^+, Na^+, K^+ and Mg^{2+}). For the following adsorption experiments, the four MFIs affected by this phenomenon were before re-exchanged in physiological solution (principal cation: Na^+). EDX-measurement confirmed that all different cationic forms converge to a ZSM-5 modification with charge compensating cations in equilibrium with the physiological medium (H^+Na^+-, Na^+-, K^+Na^+- and $Mg^{2+}Na^+$-MFIs, respectively).

Adsorption experiments with the four re-exchanged MFIs were then finally performed in aqueous solution and in physiological solution (DPBS, also in physiological solution containing urea at uremic concentrations (38 mM)) with otherwise the same experimental conditions: In both cases no significant changes of affinity can be found anymore (Fig. 10). This confirms that the change of affinity towards p-cresol of the different cationic forms of the ZSM5s initially found was actually caused by simultaneous ionic re- exchange during the adsorption process.

To further approach a physiological system, the influence of other toxins capable to co-adsorb has been studied. Common free soluble toxins such as creatinine and uric acid do not adsorb onto MFI (Wernert et al. 2005), however, urea is small enough to penetrate the channel system while it's concentration in blood is relatively high. As already mentioned, adsorption isotherms of p-cresol onto MFIs were performed in water and physiological saline buffer solution (DPBS) without and with urea at a concentration value of 38 mM.



(a)

(b)

Fig. 8 (Color online) Snapshots of the last configuration obtained at saturation of p-cresol into silicalite. Color scheme: *yellow*: silicon; *red*: oxygen; *green*: carbon; *white*: hydrogen. (**a**) The van der Waals representation corresponds to p-cresol located in the straight channels whereas those located in the zigzag channels are in stick representation. (**b**) The van der Waals representation corresponds to p-cresol located in the zigzag channels whereas those located in the straight channels are in stick representation

The corresponding points on the isotherms are already given in Fig. 10: the change of affinity with respect to samples not exposed to urea is in error range. It means that p-cresol/MFI couple is not affected by the urea presence at uremic concentration.

The adsorption results of p-cresol/MFI couple are very encouraging for further measurements in media containing amino-acids, peptides, glucids, lipids and proteins in physiological concentrations, because, even if other adsorbents such as activated carbon reach comparable adsorption levels (Wernert et al. 2005), their adsorption is not as specific, which will cause major problems in blood serum applications.

4 Summary and conclusions

This study shows that MFI-type zeolites are good absorbents for p-cresol with high adsorption capacities. In vitro test show an elimination rate around 85% of p-cresol in uremic concentration range. Changing the physical and chemical properties of the MFIs can modify the adsorption properties and especially the affinity. During p-cresol adsorption

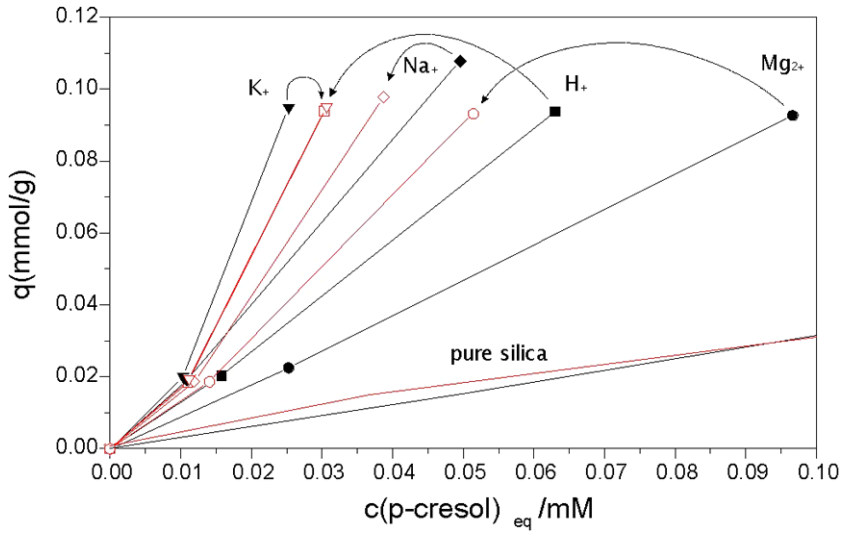


Fig. 9 Overlay of discrete points on the adsorption isotherms of p-cresol in aqueous solution (*filled points*) and in saline solution ((NaCl 9 $g \cdot L^{-1}$, *hollow points*) of pure silica and ion exchanged MFIs (H-MFI, K-MFI, Na-MFI and Mg-MFI, Si/Al = 30.4—exposed for 12 hours at 37 °C under stirring conditions)

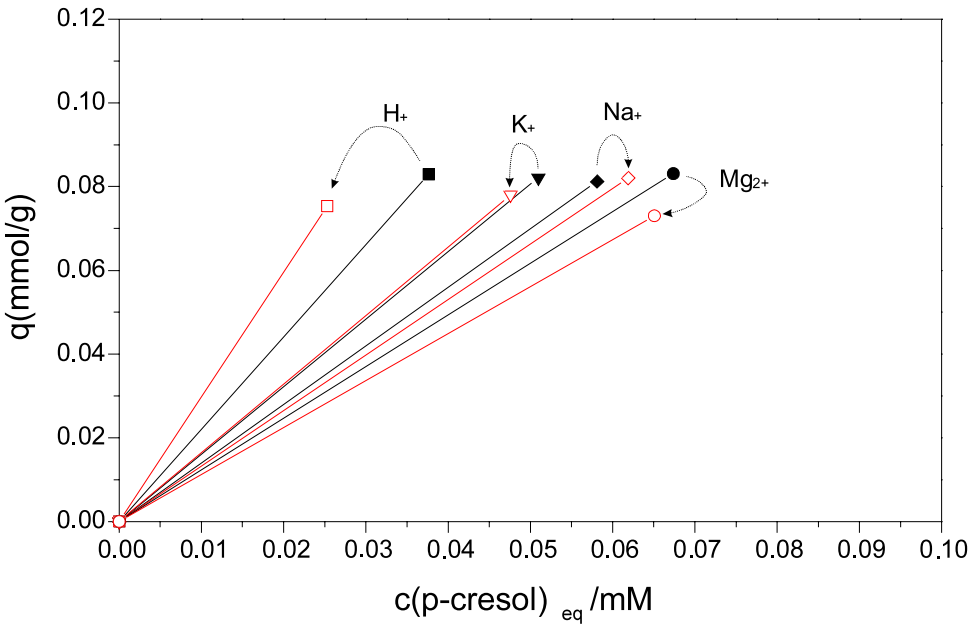


Fig. 10 Re-ion exchanged MFIs (ion re-exchange of H^+, K^+, Na^+ and Mg^{2+} MFI versus Na^+ in physiological saline buffer solution of DPBS—12 hours at 37 °C). Overlay of discrete points on the adsorption isotherms of p-cresol in aqueous solution (*filled points*) and in DPBS (*hollow points*) both containing urea (38 mM) of H^+Na^+-, Na^+-, K^+Na^+- and $Mg^{2+}Na^+$-MFIs, Si/Al = 30.4—exposed for 12 hours at 37 °C under stirring conditions)

process, co-adsorption of water in an initially hydrophobic MFI (silicalite) takes place. The adsorption behavior of p-cresol/MFIs couple is not affected by urea presence. Moreover, this couple can be used as a model system in investigations on other toxin/zeolite couples. However, for a Si/Al ratio given in a zeolite, the charge compensating cation is fixed by the equilibrium established by the physiological solution. In consequence under these conditions trimming the zeolites adsorption affinity by replacing the charge compensating cations is of low efficiency.

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References

Cerius^2, Version 4.9. Accelrys, San Diego, CA, USA (2003).
de Vos Burchart, E.: Ph.D. Thesis, Studies on Zeolites: Molecular Mechanics, Framework Stability and Crystal Growth, Table I, Chap. XII (1992)
Denoyel, R.: Colloids Surf. A **205**, 61–71 (2002)
Dou, L., Cerini, C., Brunet, Ph., Guilianelli, C., Moal, V., Grau, G., De Smet, R., Vanholder, R., Sampol, J., Berlan, Y.: Kidney Int. **62**, 1999–2009 (2002)
Eroshenko, V., Regis, R.C., Soulard, M., Patarin, J.: J. Am. Chem. Soc. **123**, 8129–8130 (2001)
Guth, J.L., Delmotte, L., Soulard, M., Brunard, N., Joly, J.F., Espinat, D.: Zeolites **12**(8), 929–935 (1992)

Humphrey, W., Dalke, A., Schulten, K.: J. Mol. Graph. **14**, 33–38 (1996)
Lesaffer, G., De Smet, R., Lameire, N., Dhondt, A., Duym, Ph., Vanholder, R.: Nephrol. Dial. Transplant. **15**, 50 (2000)
Limousin, G., Gaudet, J.-P., Charlet, L., Szenknect, S., Barthès, V., Krimissa, M.: Appl. Geochem. **22**, 249–275 (2007)
Llewellyn, P., Grillet, Y., Patarin, J., Faust, A.C.: Microporous Mesoporous Mater. **1**(4), 247–256 (1993)
Lyklema, J.: In: Fundamentals of Interface and Colloid Science, vol. II. Academic, San Diego (1995), Chap. 2
Mayo, S.L., Olafson, B.D., Goddard III, W.A.: J. Phys. Chem. **94**, 8897–8909 (1990)
Meier, W.M., Olson, D.H., Baerlocher, Ch.: Atlas of Zeolite Structure Types, 4th rev. edn. Elsevier, Amsterdam (1996)
Metropolis, N., Rosenbluth, A.W., Rosenbluth, M.N., Teller, A.N., Teller, E.: J. Chem. Phys. **21**, 1087–1092 (1953)
Robson, H., Lillerud, K.P.: Verified Syntheses of Zeolitic Materials, 2nd rev. edn. Elsevier, Amsterdam (2001)
Van Bekkum, H., Flanigen, E.M., Jacobs, P.A., Jansen, J.C.: Introduction to Zeolite Science and Practice, 2nd rev. edn. Elsevier, Amsterdam (2001)
Vanholder, R., et al.: Kidney Int. **63**, 1934–1943 (2003)
Wernert, V., Schäf, O., Ghobarkar, H., Denoyel, R.: Microporous Mesoporous Mater. **83**, 101–113 (2005)
Wernert, V., Schäf, O., Faure, V., Brunet, P., Dou, L., Berlan, Y., Boulet, P., Kuchta, B., Denoyel, R.: J. Biotechnol. **123**, 164–173 (2006)