RESEARCH LETTER

Ionic liquid modification of zeolite and its removal of chromate from water

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This study focused on using imidazolium of different chain lengths to modify the negatively charged zeolite. The modification involves a cation exchange process of the organic cations of ionic liquids (ILs) for the alkali and alkaline earth elements on zeolite surfaces. X-ray diffraction analyses revealed that the uptake of ILs was on the external surfaces. Fourier transform infrared analyses showed that different mechanisms were attributed to IL uptake on zeolite at below and above the external cation exchange capacity. After modification, the zeolite reversed its surface charge to positive, thus enhancing adsorptive removal of anionic contaminants such as chromate from water. At the same time, the modified zeolite increased their total organic carbon content, and thus could promote better adsorptive removal of hydrophobic organic contaminants from water, too. These features enable IL-modified zeolite to be used as inexpensive sorbents for the removal of multi-types of contaminants from water simultaneously.

Keywords: adsorption; anion exchange; chromate; ionic liquid; removal; zeolite

1. Introduction

Ionic liquids (ILs), due to their unique properties, have attracted much attention in the scientific community (chemists, biologists, and other related workers) during the past two decades (1). They have a vanishingly small vapor pressure, making them an attractive alternative to the volatile organic solvents (2). Although most of the use of ILs was limited as solvents for organic synthesis (3), recent application of ILs was extended to sequestration of carbon dioxides (4). Incorporating ILs into surfactant-modified zeolite MCM-41 increased CO\textsubscript{2} adsorption capacity by 2.5 times compared with surfactant-modified MCM-41 alone (5).

Imidazolium has been the most studied cation for the modification of materials due to its excellent properties shown for extraction and separation in liquid state (6). Modification of silica by imidazole increased its Cr(VI) uptake significantly (7). Moreover, magnetic nanoparticles modified with ILs showed specific extraction efficiency to organic pollutant and polycyclic aromatic hydrocarbons (8). Modification of Ca-montmorillonite (MMT) with imidazolium of different chain lengths increased its chromate sorption capacity from essentially none to 190 mmol/kg (9).

Certain types of ILs have strong affinity to negatively charged clay minerals and zeolites, and thus could be used as modifiers to enhance the removal of anionic and organic contaminants from water. Most of the studies on materials modification by ILs were limited to clay minerals. Adsorption of 1-octadecyl-3-methylimidazolium (ODMIM) into the interlayer of sodium MMT was attributed to an ion-exchanging reaction; and as the amount of adsorbed ODMIM in the interlayer of MMT increased, the aggregative structures of ODMIM become more ordered, leading to an obvious increase of the interlayer distance of MMT (10). At ODMIM loading of 2.0 times the cation exchange capacity (CEC), MMT became hydrophilic due to the formation of ODMIM bilayers on the surface of MMT (11).

With dimethyl sulfoxide as the precursor, ILs could intercalate into kaolinite resulting in a \( d \)-spacing expansion to 1.35 nm (12). Interactions of 1-dodecyl-3-methylimidazolium (DDMIM) chloride with two sulfonated anionic dyes, azoaramine G and methyl orange, resulted in considerable shifts in their spectra in both acidic and basic media (13). Smectite-like materials modified by ILs showed elevated adsorption of tetracycline and was attributed to cation exchange (14). Sequential modification of anionic and cationic
clays with a single IL solution was demonstrated and the modification method minimized the formation of waste, toxic solutions that are to be discarded through their reuse in the modification of cationic or anionic nanoclays (15).

The goal of this study was focused on evaluating zeolite modification by ILs under batch experimental conditions in conjunction with Fourier transform infrared (FTIR) and X-ray diffraction (XRD) analyses to determine the surface configuration of the green solvent on zeolite. In addition, the capability of modified materials for the removal of anionic contaminants was assessed in batch and column tests. It was expected that the combination of superior contaminant removal properties of an earth material, zeolite, with the newly developed green solvent ILs could achieve simultaneous removal of metal anions, hydrophobic organic contaminants, and bacteria and pathogens. The synergistic combination will not only expand the use of zeolite to a broader field of applications in groundwater remediation but also extend the application of green solvent for water treatment.

2. Materials and methods

2.1. Materials

The zeolite used in this study was obtained from the St. Cloud mine in Winston, New Mexico. It contained 74 ± 4% of clinoptilolite, 12 ± 2% feldspar, 12 ± 2% quartz, and 5 ± 2% smectites (16). Its major exchangeable cations were K⁺ and Ca²⁺. The particle size of the zeolite aggregates was between 1.4 and 2.4 mm. Its external surface area determined by N₂ adsorption was 15.7 m²/g (16). The external cation exchange capacity (ECEC) was between 90 and 110 mmol/kg (17). The zeolite was used as received without further pretreatment for surface modification and subsequent chromate adsorption and transport experiments.

The ILs used were DDMIM chloride (CAS#: 114596-84-5) and 1-hexadecyl-3-methylimidazolium (HDMIM) chloride (CAS#: 61546-01-8), with their critical micelle concentrations of 15 and 1.3 mmol/L, respectively (18, 19). Both were purchased from Acros and were also used as received. The chromate used was K₂CrO₄ from Fisher Scientific (Pittsburg, PA).

2.2. Batch adsorption of ILs on zeolite

For the IL adsorption isotherm study, 10 mL of IL solution at varying concentrations and 1.0 g of zeolite were added to each 50-mL centrifuge tube and the mixtures were shaken on a reciprocal shaker at 150 rpm for 24 h. After equilibration, the mixtures were centrifuged at 4000 rpm for 20 min and the supernatant was passed through 0.45-µm filters before being analyzed by an UV-vis spectrophotometer. The release of exchangeable cations accompanying IL uptake was monitored by ion chromatography (IC). All experiments were run in duplicate.

2.3. Preparation of IL-modified zeolite (ILMZ)

A large batch was prepared based on the IL adsorption capacity determined from batch tests. To each of four 250-mL centrifuge bottles, 30 g of zeolite and 200 mL of 30 mmol/L IL solution were combined. The mixture was shaken at room temperature at 150 rpm for 24 h, centrifuged at 4000 rpm for 20 min, and the supernatant was removed, followed by washing the mixture with two portions of deionized (DI) water. The IL and counterion Cl⁻ concentrations in the supernatant and subsequent washes were determined by UV-vis and IC. The ILMZ was allowed to air dry. The final IL and Cl⁻ loadings were 190 ± 0.5 and 85 ± 3 mmol/kg, respectively.

2.4. Batch study on chromate removal

In each 50-mL centrifuge tube, 2 g ILMZ and 10 mL chromate solution with initial concentrations varying from 0.22 to 4.3 mmol/L were combined. The mixtures were shaken at room temperature at 150 rpm for 24 h, and then centrifuged at 4000 rpm for 20 min. The supernatants were passed through 0.45-µm filters before being analyzed for equilibrium chromate concentration using the EPA method 7196A. Chromate removal was determined from the difference between the initial and the final solution concentrations. The release of counterion Cl⁻ due to replacement by chromate was monitored by IC. All experiments were performed in duplicates.

2.5. Column tests on chromate transport

The raw zeolite and ILMZ were packed in plastic columns (diameter = 2.6 cm) in duplicates to a height of 10.5 cm. The columns were fed with DI water until full saturation as determined by maintaining constant weight between two or more continuous measurements. Chromate solution at a concentration of 100 mg/L was delivered via a four-head peristaltic pump in an upward direction at a flow rate about 32 mL/h until full breakthrough. Then DI water was fed to study the desorption of chromate. The experiments lasted for 15 and 80 h for chromate transport through raw zeolite and ILMZ columns.

2.6. Simulation of chromate transport

HYDRUS-1D version 2.01 (20), which uses the following partial differential equation to describe the transport
of a solute undergoing equilibrium adsorption, was used to simulate the chromate breakthrough data:

\[
\frac{\partial C}{\partial t} + \rho_b \frac{\partial S}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x}
\]  

(1)

where \(C\) and \(S\) are the solute concentrations in aqueous and on solid phases, \(t\) the travel time, \(\rho_b\) the media bulk density, \(\theta\) the porosity, \(D\) the hydrodynamic dispersion coefficient, \(v\) the mean pore velocity, and \(x\) the travel distance. As the adsorption of chromate on ILMZ followed the Langmuir adsorption isotherm:

\[
S = \frac{K_LS_mC}{1 + K LC}
\]

(2)

where \(S_m\) is the solute adsorption capacity or adsorption maximum and \(K_L\) the Langmuir coefficient; the retardation factor of chromate, whose adsorption on ILMZ is governed by the Langmuir adsorption isotherm, is a function of effluent chromate concentration:

\[
R = \frac{\rho_b}{\theta} \frac{S_mK_L}{(1 + K_L C)^2}
\]

(3)

2.7. Methods of analyses

The equilibrium DDMIM and HDMIM concentrations were analyzed using a UV-vis method with a Milton Roy Spectronic 601 spectrophotometer (Ivyland, PA) at a wavelength of 228 nm. The calibration was made using standards of 0.15–1.2 mmol/L with a coefficient of termination \(r^2 = 0.997\).

Desorption of metal cations accompanying IL uptake was analyzed using an IC with a mobile phase of 3.5 mM cupric sulfate and a PRP-X200 cation chromatographic column. At a flow rate of 2.0 mL/min, the retention time was 1.4, 1.9, 2.9, and 3.9 min for Na\(^+\), K\(^+\), Mg\(^{2+}\), and Ca\(^{2+}\), respectively. The detection limit was 0.05 mM for the cations and the linear range was from 0.1 to 1 mM.

Powder XRD analyses were performed on a Rigaku D/Max-IIIa diffractometer with Ni-filtered CuK\(\alpha\) radiation at 30 kV and 20 mA. Samples were scanned from 2\(^{\circ}\) to 62\(^{\circ}\) at 1\(^{\circ}\)/min with a scanning step of 0.01\(^{\circ}\)/step. A 1\(^{\circ}\) divergent slit and scatter slit and 0.3 mm (0.1\(^{\circ}\)) receiving slit were used.

FTIR spectra were acquired on a Jasco FT/IR-4100 spectrometer equipped with a ZnSe attenuated total reflection accessory. The spectra were obtained from 650 to 4000 cm\(^{-1}\) by accumulating 256 scans at a resolution of 4 cm\(^{-1}\).

3. Results and discussion

3.1. IL uptake on zeolite

Adsorption of HDMIM on zeolite fitted the Langmuir adsorption isotherm well with an adsorption capacity of 192 mmol/kg and a \(K_L\) of 17.2 L/mmol (Figure 1). Accompanying HDMIM adsorption, the amount of counterion Cl\(^-\) adsorbed reached 94 ± 8 mmol/kg. Desorption of total exchangeable cations accompanying HDMIM adsorption followed a linear relationship up to 110 mmol/kg of HDMIM adsorption (Figure 2). As the amount of counterion Cl\(^-\) adsorbed was about half of that of HDMIM adsorption, the adsorbed HDMIM would form a bilayer configuration as was observed in hexadecyltrimethylammonium (HDTMA) adsorption on the same zeolite (17).

In comparison to HDMIM adsorption, DDMIM adsorption reached a capacity of 161 mmol/kg with a much lower \(K_L\) of 1.5 L/mmol (Figure 3). Similar to HDMIM adsorption, desorption of total exchangeable cations accompanying DDMIM also followed a linear relationship up to 110 mmol/kg (Figure 3). These results further confirmed that the initial uptake of ILs on zeolite was attributed to surface cation exchange as the ECEC of the zeolite was 110 mmolc/kg (17).

3.2. Chromate adsorption on ILMZ

Chromate adsorption on ILMZ also followed the Langmuir type isotherm with a Langmuir adsorption coefficient of 26 L/mmol (Figure 4). However, the adsorption capacity was only 22 mmol/kg in comparison to 192 mmol/kg for HDMIM adsorption on zeolite. Similarly, the adsorption of chromate on HDMIM-modified Ca-MMT was 190 mmol/kg in comparison to 2000 mmol/kg for HDMIM adsorption on the MMT (9). Desorption of counterion Cl\(^-\) accompanying chromate adsorption also followed a straight line relation (Figure 4). The greater than
1 slope may indicate that part of the chromate adsorbed was in divalent form, while the nonzero intercept might be due to overbalanced counterions during the modification stage (17). These results were similar to those for chromate adsorption on surfactant-modified zeolite (SMZ), confirming the same surface anion exchange mechanism for chromate uptake (17).

3.3. XRD analyses
The crystalline HDMIM had a few sharp peaks at 3°, 6°, 16°, and 19° 2θ (Figure 5). After adsorption on zeolite, these peaks disappeared, suggesting that the removal of HDMIM from solution by zeolite was not due to HDMIM precipitation. Instead, the surface adsorption and random arrangement of the adsorbed HDMIM molecules on zeolite were attributed to the absence of these peaks on XRD patterns. Moreover, as the d-spacing of major zeolite peaks did not change before and after IL modification, it was suggested that the uptake of ILs was on external surfaces in comparison to intercalation into the interlayer spaces of MMT (9–11).

3.4. FTIR analyses
For crystalline HDMIM, the bands at 2916 cm\(^{-1}\) corresponded to the asymmetrical stretching vibration of C–H of methylene, and the bands at 2851 cm\(^{-1}\)
belonged to the C–H symmetrical stretching vibration (21). At the monolayer adsorption, these bands were located at 2928 and 2855 cm\(^{-1}\) (Figure 6a), reflecting a strong electrostatic interaction. They shifted progressively to low wave numbers as the amount of HDMIM loading increased beyond the monolayer coverage, due to hydrophobic interactions (22). The bands at 1474 cm\(^{-1}\) were assigned to \(-\text{CH}_2\) deformation vibration (21). There is no shift of the band position as the amount of HDMIM loading increased (Figure 6b), suggesting no interactions between the mineral surface and the \(-\text{CH}_2\). The intensity of these bands did not change after the uptake of chromate from 100 and 500 mg/L solution (Figure 6c), suggesting the stability of the adsorbed HDMIM on the surface of zeolite. This result agreed well with the weak desorption of ODMIM from MMT surface (23).

3.5. Column chromate transport

Raw zeolite showed no retention of chromate as the retardation factor \(R\), as defined by the number of pore
volumes (PVs) at which the ratio of effluent chromate concentration \((C)\) to the input concentration \((C_0)\) was half (Figure 7a and 7b). In contrast, at \(C/C_0 = 0.5\), the number of PVs was about 15–17 (Figure 7c and 7d), suggesting significant retardation of chromate transport through ILMZ. For raw zeolite, fitting the experimental data by HYDRUS-1D resulted in a dispersion of 0.07 cm. In contrast, the dispersion increased to \(2 \times 10^3\) cm for ILMZ. The Langmuir adsorption coefficient from the column test agreed well with the batch study at 14–27 L/mmol. Mass balance at the end of chromate transport experiment showed that about 300 mg/kg of chromate was retained on the surface of ILMZ (Figure 7).

3.6. Mechanism of IL uptake on zeolite and chromate adsorption by ILMZ

Adsorption of ILs was attributed to hydrogen bonds, electrostatic, and \(\pi \ldots \pi\) interaction with the organic matter and the clay minerals of the soils, and stronger IL adsorption only occurs in soils with higher total organic carbon content \((24)\). The mean free energy values of IL adsorption on kaolinite were below the values of a typical ion exchange process, suggesting that the adsorption mechanism was attributed to a combination of electrostatic interaction and physical adsorption \((25)\). On the contrary, the uptake of ILs by MMT was attributed to chemical adsorption \((11)\) and by cation exchange and supplemented by hydrophobic interaction \((9)\). For kaolinite, it was speculated that the uptake of ILs at the beginning of the binding process, i.e. formation of a monolayer, was via ion exchange and van der Waals interactions, whereas at higher concentrations of ILs, dispersive interactions became dominant \((25)\).

The DDMIM and HDMIM form cations in solution and these organic cations often had high affinities for negatively charged mineral surfaces than inorganic cations. In this study, the stoichiometric release of exchangeable cations accompanying IL adsorption strongly supported a cation exchange mechanism for IL uptake, up to its ECEC (Figures 1–3). Beyond the ECEC, further uptake of ILs on the zeolite could be associated with admicelle adsorption as the amount of exchangeable cations released was reduced drastically while the amount of counterion \(\text{Cl}^-\) adsorption increased significantly (Figures 1–3). The Gibbs free energy values for the adsorption of ILs on soils also suggested a physical adsorption with exothermic effect \((24)\).

In a previous study, it was found that increased alkyl chain length did not lead to increased adsorption, indicating that hydrophobic interactions were
not the most important adsorption mechanism (26). However, in this study, a higher adsorption capacity was found when HDMIM was used in comparison to DDMIM, suggesting that a longer chain length on the tail group of the ILs would enhance the admicelle adsorption via hydrophobic interactions between the tail groups. For multilayer adsorption to occur, saturation of the second layer could only be achieved with longer alkyl chain length and the shorter alkyl chain cations would not reach saturation (27).

It has been shown that ILs could intercalate into vermiculite with a chain length of four carbons and two carbons resulting in a d-spacing of 1.18 nm only (28), into MMT with the adsorbed imidazolium ring parallels to the MMT inner surface (11). Intercalation of HDMIM into Ca-MMT resulted in a d-spacing expansion to 4.17 nm (9). In this study, the invariable d-spacing of XRD patterns suggested surface adsorption instead of intercalation. And the adsorbed ILs form admicelles as revealed by the co-adsorption of counterion Cl\(^-\) accompanying ILs adsorption. With this type of surface admicelles, the charge was reversed to positive as evidenced by zeta potential measurement (29) and balanced by counterion Cl\(^-\) when the IL loading was higher than the CEC values of the mineral. The instantaneous adsorption of chromate and the stoichiometric desorption of counterion Cl\(^-\) accompanying chromate adsorption strongly suggested a surface anion exchange mechanism (Figure 4). The anion exchange of chromate for Cl\(^-\) was more thermodynamically favored in comparison for Br\(^-\) as the counterion for SMZ (17).

Previous work indicated that adsorption of chromate by SMZ was due to surface anion exchange:

\[
2(\text{ILMZ} - \text{Cl}^-) + \text{CrO}_4^{2-} = (\text{ILMZ})_2 - \text{CrO}_4 + 2\text{Cl}^- \quad (4)
\]

where ILMZ-Cl and (ILMZ)_2-CrO_4 are IL bilayers on zeolite surfaces balanced by countermers Cl\(^-\) and CrO_4\(^{2-}\), respectively. The Kerr selectivity coefficient for chromate (\(K_K\)) over Cl\(^-\) is given by:

\[
K_K = \frac{[(\text{ILMZ})_2 - \text{CrO}_4][\text{Cl}^-]^2}{[\text{ILMZ} - \text{Cl}^-][\text{CrO}_4^{2-}]} \quad (5)
\]

The square brackets denote concentrations in mmol/L for the solution phase and mmol/kg for the adsorbed phase. The calculated \(K_K\) value is 1.2, much larger than chromate adsorption on surfactant-modified illite and MMT (30).

This anion exchange mechanism would enable the ILMZ to be used as a strong anion exchanger for separation and enrichment of other inorganic or organic anions. It is also anticipated that the materials could be regenerated after saturation of adsorbed anions (31). As most of the inexpensive earth materials do not bear positive charges on their external surfaces, the ILMZ would be utilized in wastewater treatment to remove undesired anions with a larger capacity.

4. Conclusions

Uptake of ILs on zeolite was attributed to a combination of two mechanisms. When the loading of IL on zeolite was less than the EEC of zeolite, cation exchange dominated. Above the EEC, tail–tail hydrophobic interaction was responsible for the uptake of the second layer of the admicelle formation on zeolite. Longer chain length facilitated better admicelle formation. The uptake of chromate by ILMZ was due to surface anion exchange between chromate and counterion Cl\(^-\). The combination of inexpensive earth material zeolite with green solvent ILs would enable the product to be utilized in wastewater treatment or groundwater remediation to remove undesired anions with a larger capacity.

References

(1) Suresh, J.S.; Sandhu. Green Chem. Lett. Rev. 2011, 4, 289–310.
(2) Gorman-Lewis, D.J.; Fein, J.B. Environ. Sci. Technol. 2004, 38, 2491–2495.
(3) Seddon, K.R., Rogers, R.D., Eds.; Ionic Liquids: Industrial Applications for Green Chemistry; (Proceedings of ACS symposium in San Diego, 1–5 April 2001), ACS Symposium Series 818; ACS: Washington, DC, 2002.
(4) Udayakumar, S.; Lee, M.-K.; Shim, H.-L.; Park, S.-W.; Park, D.-W. Catal. Commun. 2009, 10, 659–664.
(5) Fu, G.-H.; Lv, G.-X.; Ma, J.-T. J. Mol. Catal. 2013, 27, 218–226.
(6) Vidal, L.; Riekola, M.-L.; Canals, A. Anal. Chim. Acta. 2012, 715, 19–41.
(7) Wang, Z.; Ye, C.; Wang, X.; Li, J. Appl. Surf. Sci. 2013, 287, 232–241. http://dx.doi.org/10.1016/j.apsusc.2013.09.133
(8) Li, Y.; Tang, N.; Inagaki, F.; Mukai, C.; Hayakawa, K. J. Chem. 2013, Article ID 861021. http://dx.doi.org/10.1155/2013/861021
(9) Li, Z.; Jiang, W.-T.; Chang, P.-H.; Lv, G.; Xu, S. J. Hazard. Mater. 2014, 270, 169–175.
(10) Ding, Y.-S.; Wang, S.-S.; Zha, M.; Wang, Z.-G. Acta Phys.-Chim. Sin. 2006, 22, 548–551.
(11) Ding, Y.; Zhang, X.; Xiong, R.; Wu, S.; Zha, M.; Tang, H. Eur. Polym. J. 2008, 44, 24–31.
(12) Letaief, S.; Detellier, C. J. Mater. Chem. 2005, 15, 4734–4740.
(13) Safavi, A.; Abdollahi, H.; Maleki, N.; Zeinali, S. J. Colloid Interface Sci. 2008, 322, 274–280.
(14) Srivastava, R.; Fujita, S.; Arai, M. Appl. Clay Sci. 2009, 43, 1–8.
(15) Ha, J.U.; Xanthos, M. Green Chem. Lett. Rev. 2011, 4, 103–107.
(16) Sullivan, E.; Hunter, B.; Bowman, R.S. Clays Clay Miner. 1997, 45, 42–53.
(17) Li, Z.; Bowman, R.S. Environ. Sci. Technol. 1997, 31, 2407–2412.
(18) Jungnickel, C.; Luczak, J.; Ranke, J.; Fernández, J.F.; Müller, A.; Thöming, J. Colloids Surf. A. 2008, 316, 278–284.
(19) Preiss, U.; Junngickel, C.; Thoming, J.; Krossing, I.; Luczak, J.; Diedenhofen, M.; Klamt, A. Chem. Eur. J. 2009, 15, 8880–8885.
(20) Simunek, J.; Sejna, M.; van Genuchten, M. Th The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media; US Salinity Laboratory, USDA-ARS; Riverside, CA, 1998.
(21) Zhang, G.; Tao, L.; Zhang, G. Chinese J. Chem. Engineer. 2008, 16, 631–634.

(22) Li, Z.; Jiang, W.-T.; Hong, H. Spectrochim. Acta A. 2008, 71, 1525–1534.
(23) Matzke, M.; Thiele, K.; Müller, A.; Filser, J. Chemosphere. 2009, 74, 568–574.
(24) Studzińska, S.; Sprynskyy, M.; Buszewski, B. Chemosphere. 2008, 71, 2121–2128.
(25) Mrozik, W.; Jungnickel, C.; Skup, M.; Urbaszek, P.; Stepnowski, P. Environ. Chem. 2008, 5, 299–306.
(26) Beaulieu, J.J.; Tank, J.L.; Kopacz, M. Chemosphere. 2008, 70, 1320–1328.
(27) Stepnorski, P.; Mrozik, W.; Nichhauser, J. Environ. Sci. Technol. 2007, 41, 511–516.
(28) Cui, W.-F.; Gao, X.-H.; Wang, Y.-P. Asian J. Chem. 2010, 22, 911–920.
(29) Markiewicz, M.; Mrozik, W.; Rezwan, K.; Thoming, J.; Hupka, J.; Jungnickel, C. Chemosphere. 2013, 90, 706–712.
(30) Li, Z. J. Environ. Qual. 1999, 28, 1457–1463.
(31) Li, Z.; Bowman, R.S. Water Res. 2001, 35, 322–326.