Stability and pH-independence of nano-zero-valent iron intercalated montmorillonite and its application on Cr(VI) removal

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ABSTRACT

Composite of nano-zero-valent iron and montmorillonite (NZVI/MMT) was prepared by inserting NZVI into the interlayer of montmorillonite. The unique structure montmorillonite with isolated exchangeable Fe(III) cations residing near the sites of structural negative charges inhibited the agglomeration of ZVI and result in the formation of ZVI particles in the montmorillonite interlayer regions. NZVI/MMT was demonstrated to possess large specific surface area and outstanding reducibility that encourage rapid and stable reaction with Cr (VI). Besides, the intercalation also makes NZVI well dispersed and more stable in the interlayer, thereby improving the reaction capacity by 16 times. The effects of pH value, initial concentration of Cr (VI) and reaction time on Cr (VI) removal have also been investigated in detail. According to PXRD and XPS characterization, NZVI/Cr (VI) redox reaction occurred in the interlayer of MMT. The study of NZVI/MMT is instrumental to the development of remediation technologies for persistent environmental contaminants.

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1. Introduction

Chromium compounds are widely used in various sectors of the industry (Mohan et al., 2006; Olmez, 2009). Chromium (Cr) can be released to the environment both by the anthropogenic and natural processes, where the natural sources of Cr include volcanic eruptions and weathering of rocks (Serpone et al., 1988). Cr is a major industrial pollutant whose concentration in the environment keeps increasing due to its extensive use in leather tanning, stainless-steel production, and electroplating (Kantar et al., 2008). Consequently, Cr contamination has spread in the environment and affected drinking water resources. Although chromium can exist in various oxidation states ranging from Cr(II) to Cr(VI), the most common oxidation states in natural systems are Cr(III) and Cr(VI). Commonly found in contaminated groundwater, soil and industrial wastewater, the hexavalent form, Cr(VI), is toxic and carcinogenic to human and animals and may be more toxic than its trivalent form, in Cr(III) compounds (Lalvani et al., 1998). Reduction of Cr(VI) to Cr(III) followed by precipitation is regarded as a satisfactory solution in eliminating the toxicity of Cr(VI) since the toxicity of trivalent Cr towards a living cell is 500–1000 times less than hexavalent Cr (Costa, 2003). Cr(VI) is highly soluble, mobile and toxic, while Cr(III) is relatively insoluble, immobile and less harmful (Fu and Wang, 2011; Mondal, 2009). Therefore, the development of technologies to remediate Cr(VI) contaminated sites is of great importance (Lee et al., 2009, Li et al., 2006; Sun et al., 2006). Conventional pump-and-treat remediation method may involve pumping contaminated groundwater to the surface for treatment prior to its safe disposal. This approach, however, has proved to be expensive and ineffective in achieving the acknowledged level of cleanup (Lee et al., 2009). Thus, it is necessary to develop a more effective technology to remove Cr (VI) from contaminated aquifers.

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Nanoscale Zero-Valent Iron (NZVI) has shown good potential in the removal of metals and other aqueous pollutants (Li et al., 2006; Ling et al., 2012; Sun et al., 2006; Wu et al., 2013). The physicochemical properties and reductive capacity of NZVI can facilitate rapid decontamination of polluted water (Li et al., 2006; Sun et al., 2006). Unfortunately, NZVI often forms aggregates, which decreases its efficiency due to the significant decline in its specific surface area (Wei et al., 2012) that, in turn, may result in a less negative oxidation - reduction potential (Shi et al., 2011a, 2011b). As such, preventing NZVI aggregation to enhance its stability and performance remains a technical challenge (Liu and Lowry, 2006; Liu et al., 2007; Phenrat et al., 2006). In addressing the issue, NZVI immobilization on mechanical supports such as resins (Ponder et al., 2000, Ponder et al., 2001), and porous carbon (Hoch et al., 2008; Sunkara et al., 2011; Zhan et al., 2011) has been demonstrated; further, to prevent NZVI aggregation, its stabilization by polyelectrolytes such as carboxymethylcellulose (CMC) (He and Zhao, 2005) and polyvinyl pyrrolidone (PVP) (Sakulchaicharoen et al., 2010) has also been attempted. For example, it has been demonstrated that the removal rates of Cr (VI) and Pb (II) by resin-supported NZVI increased 5- and 18-fold, respectively, in comparison to that by bare (unsupported) NZVI (Ponder et al., 2000, Ponder et al., 2001). NZVI has also been incorporated into silica particles (Zheng et al., 2008) using an aerosol-assisted process and subsequent reduction that showed a more efficient TCE treatment by the unaggregated or dispersed NZVI. These results indicate that treatment of contaminants by supported NZVI is a promising approach for remediation of contaminated sites (Hoch et al., 2008; Sunkara et al., 2011; Zhan et al., 2008; Zhan et al., 2011; Zheng et al., 2008). However, the immobilization methods are often complex, and the development of a more efficient immobilization method is desirable in order to harness the true potential of NZVI in site cleanup.

In recent years, several researchers have shown that sandwich-structure montmorillonite (MMT) consisting of one octahedral Al–O sheet between two tetrahedral Si–O sheets as a supporting matrix to disperse NZVI and reduce its aggregation. In a recent study, MMT-templated NZVI had shown superior reactivity and efficiency towards nitrobenzene reduction compared to NZVI (Gu et al., 2010). The proposed mechanism of Cr (VI) removal by NZVI may involve either direct redox reaction between NZVI and Cr(VI) or indirect reduction by the corrosion products of NZVI (Fe²⁺ and H₂), where Cr removal kinetics may depend upon NZVI dispersion on the surface and in the interlayers of MMT (Cundy et al., 2008). Thus far, it remains unclear which type of NZVI dispersion plays a dominant role and how to enhance Cr removal kinetics.

In view of the above-mentioned limitations of unsupported NZVI, i.e., agglomeration and instability, a NZVI/MMT composite has been advanced in this paper that is quite stable and yet more reactive. NZVI/MMT can be prepared by reduction of Fe(III) inserted in MMT interlayers. Our results show that Cr (VI) removal capacity of NZVI/MMT is 410 mg/g, which is remarkably 16 times greater than that of unsupported NZVI (25 mg/g). In addition, NZVI/MMT shows a good removal capacity after exposed in air for 140 h with more than 85% NZVI remaining reactive, thus suggesting that the problem of agglomeration and instability of unsupported NZVI has been overcome by employing NZVI/MMT composite. According to XRD and XPS results, the redox reaction by NZVI may occur in the interlayer of MMT, whereby Fe⁰ is oxidized to Fe³⁺ and Cr⁶⁺ is reduced to Cr³⁺.

2. Materials and methods

2.1. Materials and chemicals

The montmorillonite used was SWy-2 obtained from the Clay Mineral Repositories at Purdue University (West Lafayette, IN, USA), and was used without further purification. It has a chemical formula of (Ca₀.₁₂ Na₀.₃₂ K₀.₀₅)[Al₃.₀₁ Fe(III)_₀.₄₁ Mg₀.₅₄] [Si₂.₃₈ Al₀.₀₂]O₂₀(OH)₆, a CEC of 85 ± 3 mmolc/100 g (Chipera and Bish, 2001), a layer charge of 0.32 eq/mol per (Si, Al)₄O₁₀ (Borden and Giese, 2001), an external surface area (ESA) of 23 m²/g, respectively (Mermut and Lagaly, 2001), and a mean particle size of 3.2 μm with a d₂₅ to d₇₅ in the range of 3–10 μm.

Reagents used in the study include potassium dichromate, sodium borohydride, potassium chloride, ferric chloride, ethanol, and diphenylcarbazide, purchased from various manufacturers that were all of analytical grade. The stock Cr (VI) solution was prepared by dissolving potassium dichromate in de-ionized water. The solution pH was adjusted by adding 0.1 N HCl or 0.1 M NaOH solution, and measured with a pH meter (PHS-3C, China).

2.2. Preparation of NZVI/MMT composite

The preparation of NZVI/MMT composite was carried out as the following steps: First, 0.1 mM ferric chloride solution was obtained by dissolving 30 g of FeCl₃·7H₂O into ethanol: water solution (50 mL, 4:1 v/v) in a dry conical flask. Then 5 g of montmorillonite was soaked in 50 mL of above ferric chloride in ethanol-water mixture for about 12 hrs. Subsequently, freshly prepared 100 mL of 90 mM NaBH₄ solution (3.54 g NaBH₄ dissolved in 100 mL water) was added into the conical flask containing ferric chloride solution and montmorillonite and then stirred continuously for about 20 min in N₂ environment to avoid oxidation. The formed suspension was filtered (2.2 μm pore size of the filter) and the black precipitate was washed three times with pure ethanol and dried overnight at 75 °C under vacuum.

2.3. Batch experiments for Cr (VI) removal

The effects of solution pH, initial Cr (VI) concentration, adsorption time, and NZVI/MMT concentration (loading) on Cr removal were investigated in this study. First of all, Cr (VI) calibration curves were prepared to relate Cr absorbance to its removal were investigated in this study. First of all, Cr (VI) calibration curves were prepared to relate Cr absorbance to its removal rate can be quantified using the Cr (VI) concentration in solution was...
concentration of Cr(VI) was measured by diphenylcarbazide (DPC) colorimetric method (Qian et al., 2008) using a spectro-photometric method (722sp) at wavelength of 540 nm. The removal capacity of Cr(VI) in batch experiments, as discussed later in the Results and Discussion section, can be described mg of Cr(VI) removed/g of MMT and NZVI/MMT composite.

2.4. Characterization and analysis method

The phase composition of NZVI/MMT samples was characterized by powder crystal X-ray diffraction method (XRD). The testing conditions were: tube voltage = 40 kV, tube current = 100 mA, Cu target (\( \lambda _{CuK\alpha} = 1.5418 \) Å), scanning rate = \( 8^\circ/\min \), \( 2\theta = 10^\circ \sim 100^\circ \). The oxidation state of Cr was characterized by powder crystal X-ray diffraction method (XRD). The testing conditions were: tube voltage = 40 kV, tube current = 100 mA, Cu target (\( \lambda _{CuK\alpha} = 1.5418 \) Å), scanning rate = \( 8^\circ/\min \), \( 2\theta = 10^\circ \sim 100^\circ \). The oxidation state of Cr was characterized by X-ray Photoelectron Spectroscopy analysis (XPS).

3. Results and discussion

3.1. Effect of initial concentration on Cr (VI) removal

The initial concentration of Cr(VI) may affect the reaction between Cr(VI) and NZVI/MMT, leading to an influence on Cr(VI) removal capacity. Significant changes in the initial concentration of Cr(VI), the removal capacity of NZVI/MMT can be improved to maximum. The Cr(VI) removal capacity increased significantly as initial Cr(VI) concentration increased from 10 to 200 mg/L; it reached a maximum of 19 mg of Cr(VI)/g of NZVI/MMT at 400 mg/L initial Cr(VI) concentration (Fig. 1). Since there are two components in NZVI/MMT composite, i.e., MMT and NZVI that may influence Cr(VI) removal, it was deemed necessary to examine the role of each component on Cr(VI) removal. Control experiments showed that Cr(VI) removal capacity of MMT alone is much inferior, with a maximum removal only ~1 mg of Cr(VI)/g 1 g MMT. In other words, only 5% of the total Cr(VI) removal capacity with NZVI/MMT is due to removal by MMT and the remainder appears to be due to removal by NZVI.

The removal capacity is higher when the initial Cr(VI) concentration is high. During the redox reaction, NZVI may get oxidized to Fe(III) and Cr(VI) may be reduced to Cr(III). However, if Cr(III) is in proximity to Fe(III) that can be a corrosion product, a thin film of Fe(III)–Cr(III) hydroxides can form on NZVI surface (Powell et al., 1995). The film is believed to increase the resistance for the electron transfer from NZVI to Cr(VI) and inhibit Cr(VI) reduction to Cr(III). According to a published report, the actual Fe–Cr hydroxide structure was a mixture of \( \text{Fe}_{0.667}\text{Cr}_{0.333}\text{OOH} \) and \( \text{Fe}_{0.667}\text{Cr}_{0.333}(\text{OH})_3 \) (Li et al., 2008). Also, during Cr(VI) reduction by acidic Fe(II) (aq), the surface solid is a composite of Fe(III) and Cr(III), described as \( \text{Fe}_{0.75}\text{Cr}_{0.25}(\text{OH})_3 \) (Buerge and Hug, 1999). The reactivity of sites on NZVI may decline with increasing oxidant concentration, some of which can be attributed to the passivating effect of chromate as a corrosion inhibitor.

3.2. Effect of contact time on Cr (VI) removal

The contact time of NZVI/MMT and Cr(VI) is positively correlated with the amount of Cr(VI) got removed, which may represent rate. The Cr(VI) removal increased during the course of batch experiment and the equilibrium is established in 60 min (Fig. 2). The Cr(VI) removal by NZVI alone showed removal efficiency is approximately similar to that of NZVI/MMT, where the equilibrium reached in ~60 min, suggesting that NZVI intercalation within MMT structure did not reduce Cr(VI) removal kinetics.

The inset in Fig. 2 shows Cr(VI) removal capacity normalized to NZVI concentration, contained in the interlayer of MMT. It shows that the maximum removal capacity of NZVI is 410 mg/g, which means almost half of the NZVI participates in the reaction on Eq. (1), while the maximum removal capacity of NZVI is only 25 mg/g. Not only the stability and reactivity of NZVI may increase after intercalation within MMT structure, its Cr(VI) removal capacity also increased ~16 fold. As mentioned in many other publications (Hoch et al., 2008; Shi et al., 2011a, 2011b; Wu et al., 2013), NZVI can form agglomerates and oxidizes easily, which renders the NZVI less reactive due to the surface oxide film coating. By intercalating NZVI into MMT, both its dispersion and stability improved thus leading to a dramatic increase in NZVI reactivity.

3.3. Effect of pH on Cr (VI) removal

The performance of NZVI depends on pH greatly. At pH = 3, the Cr(VI) removal capacity of NZVI/MMT at equilibrium is 15 mg/g, while that of unsupported NZVI at equilibrium is 25 mg/g. At pH = 5, however, the removal capacity of NZVI decreased by 72% to 7 mg/g, while the decrease in removal capacity of NZVI/MMT is much smaller, only ~7% (by 1 mg/g). Apparently, the Cr(VI) removal capacity of NZVI is significantly greater in strongly acid conditions, that can reduce/inhibit oxides coating on NZVI surface. On the other hand, NZVI/MMT is clearly more stable in Cr(VI) removal in comparison, and its reactivity is less dependent on pH. The performance of NZVI depends on pH greatly. At pH = 3, the Cr(VI) removal capacity of NZVI/MMT at equilibrium is 15 mg/g, while that of unsupported NZVI at equilibrium is 25 mg/g. At pH = 5, however, the removal capacity of NZVI decreased by 72% to 7 mg/g, while the decrease in removal capacity of NZVI/MMT is much smaller, only ~7% (by 1 mg/g). Apparently, the Cr(VI) removal capacity of NZVI is significantly greater in strongly acid conditions, that can reduce/inhibit oxides coating on NZVI surface. On the other hand, NZVI/MMT is clearly more stable in Cr(VI) removal in comparison, and its reactivity is less dependent on pH.

Further understanding of the effect of pH in Cr(VI) removal process, a more systematic study on the change in removal capacity of both NZVI and NZVI/MMT during a continuous change in pH was done. The pH appears to play an important role in the removal process.
role in controlling the rate of reaction since it can affect the charge on the surface of materials. The effect of pH on Cr(VI) removal by NZVI/MMT composite (Fig. 3) indicates excellent removal capacity of NZVI/MMT at pH 3-6, but it declined at pH > 7. The smallest Cr(VI) removal capacity, 5 mg/g, was observed in an alkaline environment. This suggests that the Cr(VI) removal rate increased as pH decreased, which is in agreement with previous reports (Geng et al., 2009; Yuan et al., 2009). These results demonstrate that a lower pH favored Cr(VI) reduction, since at lower pH, NZVI corrosion is accelerated and the precipitation of Cr(III) and Fe(III) hydroxides on the surface of iron is not as favorable, which leads to an increase in the reaction rate (Lee et al., 2003). Apparently, an acidic environment may favor Cr(VI) removal (Rivero-Huguet and Marshall, 2009), and can boost the reactions (equations below) (Fang et al., 2011).

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8H^+ + CrO_4^{2-} + Fe^0 \rightarrow Fe^{3+} + Cr^{3+} + 4H_2O \quad (1)
\]

\[
(1 - x)Fe^{3+} + xCr^{3+} + 3H_2O \rightarrow Cr_xFe_{1-x}(OH)_3 + 3H^+ \quad (2)
\]

\[
(1 - x)Fe^{3+} + xCr^{3+} + 2H_2O \rightarrow Cr_xFe_{1-x}OOH + 3H^+ \quad (3)
\]

Cr(VI) removal by NZVI is more pH-dependent than by NZVI/MMT as the removal capacity of NZVI declined from 25 mg/g at pH = 3 to 5 mg/g at pH = 5, which is comparable to Cr(VI) removal by NZVI/MMT under alkaline environment. On the other hand, NZVI in the interlayer of MMT is more reactive.
and less pH-dependent. Recent reports have shown that Cr(VI) removal with NZVI and other composites of NZVI are highly pH-dependent (Hoch et al., 2008; Shi et al., 2011a, 2011b; Shi et al., 2011a, 2011b; Zhu et al., 2012). Although we show that a lower pH is favorable for improved Cr(VI) removal, the experiments in this study were conducted at a near environmental pH and lower initial Cr concentration in consideration of the potential applications of this technology.

3.4. Stability

The stability of NZVI can be improved significantly by its intercalation within MMT. The content of NZVI in both NZVI and NZVI/MMT can be measured by KMnO4 method in the air. Then the rate of oxidation can be calculated based on it. In contact with air, NZVI oxidation was accomplished in 110 h (Fig. 4a). The amount of KMnO4 demand decreases from 125 mg/g (for NZVI without any exposure to air) to 10 mg/g (for NZVI already exposed to the air for 110 h), which corresponds to a decrease in the amount of NZVI from 0.012 g to 0.001 g due to its oxidation in air. After a 140 h exposure in the air, the amount of KMnO4 removed by NZVI/MMT decreases to only 10 mg/g corresponding to a 0.001 g decrease of NZVI in NZVI/MMT sample, which is probably caused by oxidation of the NZVI adsorbed on the surface of MMT.

By estimating the amount of reactive Fe0 in NZVI and NZVI/MMT with KMnO4 method, its reaction rate with oxygen can be obtained. It turns out that both NZVI and NZVI/MMT oxidizes with the pseudo-second-order kinetic models well (Fig. 4c and d). Reaction rate of bare NZVI with oxygen is relatively fast, which makes it unstable in air. A similar conclusion can be drawn from the results of Cr(VI) removal with NZVI and NZVI/MMT respectively (Fig. 4b). Cr(VI) removal capacity of NZVI decreased rapidly from 25 mg/g to 4 mg/g after its exposure to air, while that of NZVI/MMT the removal capacity does not change as much. In conclusion, after NZVI is intercalated into MMT, it tends to be more stable and reactive.

3.5. Characterization of materials

The interlayer spacing of MMT can be increased from 12.27 Å to 16.22 Å as the concentration of the Fe(III) solution that MMT was soaked in increased (Fig. 5a), indicating an increase in the amount of intercalation. Fe(III) may enter the interlayer of MMT by exchanging with Na+. Since hydrated Fe(III) has a much larger radius than Na+, the interlayer spacing of MMT can increase after Na+ is replaced by Fe(III), which was subsequently reduced to NZVI in situ in the interlayer. The interlayer spacing of NZVI-MMT showed a decrease after the in situ reduction of Fe(III) (Fig. 5b). For example, the interlayer spacing of one sample decreased from 16.22 Å to 15.17 Å after the reduction of Fe(III) to NZVI. The NZVI concentration in the composite increased as the interlayer spacing increased since greater spacing can be due to more Fe(III) intercalation, and higher NZVI concentration as a result. As such it is then reasonable to deduce that the reduction of Cr(VI) and removal by NZVI may occur in the interlayer.

The reduction mechanism of Cr(VI), which exists in the form of CrO4^2-, within the interlayer was also examined. A plausible mechanism can by the entry of H+ in the interlayer first causing charge imbalance, which can then drive CrO4^2- into the interlayer to react with NZVI. In order to prove this
hypothesis, the difference in interlayer spacing after the removal of different concentrations of Cr(VI) in both strong acidic and alkaline environment were measured. At pH = 2, the interlayer spacing increased from 12.91 Å to 14.65 Å as the concentration of Cr(VI) increased from 5 mg/L to 200 mg/L (Fig. 6a), suggesting more CrO$_4^{2-}$ entering the NZVI/MMT interlayer. However, for the same experiment completed at pH = 10, the interlayer spacing increase was smaller, from 12.74 Å to 13.22 Å (Fig. 6b). This supports our hypothesis that CrO$_4^{2-}$ entrance into the MMT interlayer may be facilitated in the presence of H$^+$. 

A full angle PXRD has been done on the samples at different stages (Fig. 7). The MMT used in this experiment was Na–MMT with an interlayer spacing of 12.27 Å, which can be increased to 14.02 Å after the intercalation with Fe(III) by ion exchange. The interlayer spacing decreased to 13.16 Å after in-situ reduction of Fe(III) to NZVI. The fact that there is no characteristic diffraction peak for NZVI presence in PXRD result suggests that almost all of the NZVI exists in the interlayer of MMT. After the Cr(VI) removal process with NZVI/MMT, the interlayer spacing increased to 15.48 Å that suggest the difference in radius of

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**Fig. 5.** X-ray diffraction patterns of different intercalating quantity (d/Å), (a) Fe$^{3+}$ –MMT and (b) NZVI/MMT.

**Fig. 6.** X-ray diffraction patterns of NZVI/MMT removal Cr (VI) in different pH, (a) pH = 2 and (b) pH = 10 (d/Å).
Fe$^{3+}$•H$_2$O. Thus the PXRD result reveals that Fe(III) that enters the interlayer was reduced to NZVI, and that its redox reaction with Cr(VI) may occur in the MMT interlayer.

X-ray photoelectron spectroscopy is an important technique to evaluate the oxidation states of Fe and Cr in the sample (Fig. 8). The Fe(III) ion after in situ reduction in the MMT interlayer has a binding energy of 706.9 eV for 2p$^{3/2}$, 720 eV for 2p$^{1/2}$, indicating its presence as NZVI (Muftikian et al., 1996; Sun et al., 2006). However, the binding energy for 2p$^{3/2}$ and 2p$^{1/2}$ increased to 710.8 eV and 725.1 eV respectively upon NZVI reaction with CrO$_4^{2-}$, which can be attributed to $\alpha$-Fe$_2$O$_3$ (Li et al., 2007, Li et al., 2009). This shows that NZVI was oxidized into Fe$_2$O$_3$ in the removal process. It has been reported that Cr(III) binding energy of 2p$^{3/2}$ and 2p$^{1/2}$ are 576.3 ~ 578.9 eV and 586.9 eV ~ 588.2 eV respectively (Liu and Terano, 2001; Rao et al., 1999; Wang et al., 2010; Yim and Nam, 2004). After reaction with NZVI, Cr binding energy of 2p$^{3/2}$ and 2p$^{1/2}$ changed to 578.4 eV and 587.73 eV respectively, indicating the presence of Cr(III), which is the reduced product. In summary, the XPS result suggests that Cr(VI) reduction to Cr(III) by NZVI occurs within MMT interlayers.
The mechanism of Cr(VI) removal with NZVI/MMT includes four steps as shown in Fig. 9: (i) Entry of Fe(III) into MMT interlayer by ion exchange; (ii) Fe(III) was reduced into NZVI in situ, and the interlayer spacing decreases as a result; (iii) surface of Fe became oxidized into Fe(II) in the acidic environment, then CrO$_4^{2-}$ enters the interlayer due to charge imbalance; (iv) as CrO$_4^{2-}$ meets with NZVI in the interlayer, NZVI loses electrons and becomes oxidized into Fe(III) and CrO$_4^{2-}$ gains electrons and gets reduced to Cr(III). The MMT interlayer spacing increased since hydrated Fe(III) and Cr(III) ions have larger radii. Though there are several steps in the removal process, the reaction of Cr(VI) removal by NZVI/MMT interlayer was rapid.

4. Conclusions

In this investigation, the NZVI/MMT composite was prepared by in-situ reduction of Fe(III) intercalated within MMT interlayers. Under acidic environment, NZVI/MMT proved to be more reactive and equilibrium can be reached in 60 min with a maximum removal capacity of 15 mg/g. The NZVI/MMT decreased only 0.001 g after exposed in air for 140 h and remains a higher reactivity makes NZVI/MMT more stable than NZVI. According to PXRD and XPS, NZVI/Cr (VI) redox reaction occurred in the interlayer of MMT with a product of Fe(III) and Cr(III). NZVI has important limitations due to its agglomeration and instability, and it may only be effective in acidic environment. On the other hand, NZVI/MMT composite shows high and sustained reactivity and unlike NZVI it is not constrained by issues of agglomeration, instability, low reactivity or pH dependency.

References
