Nano-Structured Magnesium Oxide Coated Iron Ore: Its Application to the Remediation of Wastewater Containing Lead

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Magnetically separable nano-structured magnesium oxide coated iron ore (IO\(^{MgO}\)) was prepared using environmentally benign chemicals, such as iron ore (IO), magnesium(II) nitrate hexahydrate [Mg(NO₃)₂·6H₂O] and urea; via an easy and fast preparation method. The IO\(^{MgO}\) was characterized using X-ray diffraction (XRD), field-emission scanning electron microscopy (FE-SEM), energy-dispersive X-ray spectroscopy (EDS) and alternating gradient magnetometer (AGM) analyses. The isotherm and kinetic studies indicated that IO\(^{MgO}\) has a comparably higher Langmuir constant (\(K_L\), 1.69 L mg\(^{-1}\)) and maximum sorption capacity (33.9 mg g\(^{-1}\)) for lead (Pb) than other inorganic media. Based on MgO amount, the removal capacity of Pb by IO\(^{MgO}\) was 2,724 mg Pb (g MgO\(^{-1}\)), which was higher than that (1,980 mg g\(^{-1}\)) for flowerlike magnesium oxide nanostructures reported by Cao et al. The kinetics, FE-SEM, elemental mapping and XRD results revealed that the substitution followed by precipitation was identified as the mechanism of Pb removal and plumbophyllite (Pb₂Si₄O₁₀·H₂O) was the precipitated phase of Pb. A leaching test revealed that IO\(^{MgO}\) had negligible concentrations of leached Fe at pH 4–9. Since the base material, IO, is cheap and easily available, IO\(^{MgO}\) could be produced in massive amounts and used for remediation of wastewater containing heavy metals, applying simple and fast magnetic separation.

Keywords: Wastewater, Heavy Metals, Magnetically Separable Magnesium Oxide, Adsorption, Magnetization.

1. INTRODUCTION

Heavy metal pollution from the discharge of industrial wastewater is becoming a global issue with potential long term health risks.¹ Heavy metals are highly toxic, having lethal and carcinogenic effects when their concentrations exceed the permissible levels.² Among the numerous heavy metals, lead, arsenic, cadmium, copper and nickel have been found to be the most hazardous and toxic heavy metals. Particularly, exposure to lead (Pb) is a risk factor for damage to the fetal brain, kidneys, circulatory system, and nervous system.³

The most commonly practiced techniques for removal of heavy metals from aqueous phases include precipitation, coagulation, ion exchange, and electrodialysis.⁴,⁵ However, those methods have several disadvantages such as incomplete metal removal, high capital cost and operational cost, high cost for the removal of the residual metal sludge and unsuitability for small-scale industries.⁶ Adsorption is considered to be one of the most promising technologies because of its simple and economical setup, as well as easy operation. It is most applicable in full-scale applications when a highly efficient and cheap adsorbent can be developed based on materials that are produced in large quantities.⁵,⁷

Conventional column type adsorption processes have been studied for decades. When the adsorption media in a column is saturated, it is then regenerated using specific leaching chemicals. Larger media has a higher diffusion
limit for saturated adsorption, while smaller media has a lower hydraulic conductivity. Since adsorption capacity and speed can be limited, the granular media used in the column could have a shorter lifespan than that would be expected from its equilibrium equation.

To overcome these problems, many researchers have studied a new conception of the adsorption process using magnetically-separable materials (MSMs) such as magnetite, SiO₂/Fe₂O₃, magnetite coated nano-carbon, etc. A certain size range of MSMs can be applied to not only adsorption, but also various other applications such as drug delivery, catalysis, bioseparation, data storage, magnetic resonance imaging (MRI), sewage coagulation, radionuclides removal, organic dye adsorption, and oily soil remediation.²⁻¹²

In recent years, the usage of metal oxides or metal hydroxide in removing heavy metals has attracted much interest due to their low cost, environmentally benign nature, and excellent adsorption properties.¹³⁻¹⁷ In particular, easy and low-cost synthesis of nanostructured magnesium oxide has a certain merit in treatment application because all the chemicals used are inexpensive and environmentally benign.² Due to its non-toxic property and potential of high sorption capacity, nano-particles of MgO were applied as an adsorbent not only for anions (i.e., arsenate and phosphate),¹⁵ but also for dye, heavy metals, and organic matter.¹⁶⁻²¹ However, it is difficult to put nanoparticles of MgO into a column or separate them out once saturated when used in a completely stirred tank reactor (CSTR). Up to now, there is no reported study on magnetized MgO and its usage for removing heavy metals in the aqueous phase.

In this study, magnetically-separable sub-micron iron ore (IO) was obtained from a mining site and its surface was modified with nano-structured magnesium oxide (MgO) for the purpose of Pb removal. Since IO is cheap and readily available in abundance, there is high potential for mass production of adsorbent.

The objectives of this study were (i) to synthesize nano-structured MgO coated IO (designated as IOMgO) using economically available precursors with a simple and fast synthesis route, (ii) to find out the Pb sorption capacities and kinetic rates of IOMgO, and finally (iii) to elucidate the Pb removal mechanism of IOMgO through conducting testing of various physicochemical characteristics.

2. MATERIALS AND METHODS

2.1. Preparation of Nanostructured MgO Coated Iron Ore

All chemicals including magnesium(II) nitrate [Mg(NO₃)₂·6H₂O] and urea were of the analytical grade. In the procedure, a solution of [Mg(NO₃)₂·6H₂O], and urea was prepared with the ratio of 2:1 in 25 mL of distilled water. The prepared solution was then used to coat 20 g of natural IO (10–50 μm) (obtained from an iron ore mining site) in a Teflon-lined autoclave bottle. The Teflon-lined autoclave bottle was then sonicated for about 5 min to disperse the solution over the IO surface. The autoclave was then sealed and placed in a microwave oven and heated to 150 °C for 30 min. After cooling to room temperature, the precipitate was collected as IOMgO by centrifugation and washed with distilled water. Then, the precipitate was further calcined at 400 °C for 2 h.

2.2. Characterization

X-ray diffraction (XRD) patterns were obtained using an X-ray diffractometer (PANalytical Empyrean) with Cu Kα radiation (λ = 1.54443 Å) at 40 kV and 40 mA. XRF analysis was also conducted to further ensure the existence of MgO on the surface of the IO. The microscopic features of the materials were characterized by field-emission scanning electron microscopy (FE-SEM, Hitachi SU 8000), while energy-dispersive X-ray spectroscopy (EDS) was conducted using a Bruker XFlash Detector 6/30 and high resolution transmission electron microscopy (HR-TEM). The nitrogen adsorption and desorption isotherms were measured using a Micromeritics TriStar II 3020 system. The magnetization tests were conducted using an alternating gradient magnetometer (AGM).

2.3. Pb Adsorption

Solutions with various concentrations of Pb(II) were prepared using lead nitrate. The pH value was adjusted to 5–6. For the adsorption isotherms, 0.2 g of prepared media was added to a 100 mL solution containing different initial concentrations of Pb (30–150 mg L⁻¹) under stirring for 24 h, at room temperature. Each solution had NaCl added to create a 0.1 M ionic strength. The adsorption data were fitted to the Langmuir and Freundlich isotherms as follows.

The linear form of the Langmuir model can be depicted as follows. When adsorption is held to a monolayer and uniform surface, the Langmuir model fits the isotherm data. The maximum adsorption capacity will be achieved when all sorption sites are saturated.

\[ q_{eq} = \frac{Q_{max} K_L C_{eq}}{1 + K_L C_{eq}} \] (1)

Where \( q_{eq} \) is the amount of solute adsorbed per unit weight of adsorbent (mg g⁻¹), \( C_{eq} \) is the equilibrium concentration of solute in the bulk solution (mg L⁻¹), \( Q_{max} \) is the maximum adsorption capacity (mg g⁻¹), and \( K_L \) (L mg⁻¹) is the Langmuir constant related to the energy of adsorption.

Assuming that the adsorption is held onto the heterogeneous surface of the adsorbent, the Freundlich model better fits the isotherm data. In the Freundlich model,
chemisorption and physisorption are pertinent to monolayer and multilayer adsorption, respectively. The linear form of the Freundlich equation is expressed as:

$$\log q_e = \log K_f + \frac{1}{n} \log C_e$$  \hspace{1cm} (2)

Where $K_f$ and $n$ are Freundlich isotherm constants related to adsorption capacity and adsorption intensity, respectively.

To study the adsorption kinetics, 0.2 g of prepared media was added to 100 mL of solution with an initial concentration of 60 mg L$^{-1}$. At specified time intervals, the suspension was filtered using a Whatman filter paper and the filtrate was analyzed by inductively coupled plasma-optical emission spectroscopy (ICP-OES, PerkinElmer OPTIMA 8300) to measure the Pb concentration remaining in the solution.

After obtaining the kinetic data, the pseudo-second order kinetic model equation was applied to obtain the kinetic constants of the reaction:

$$\frac{t}{q_t} = \frac{1}{K_2q_e^2} + \frac{t}{q_e}$$  \hspace{1cm} (3)

Where $K_2$ is the rate constant of pseudo second-order adsorption (g mg$^{-1}$ min$^{-1}$) and $K_2q_e^2$ or $q_v$ (mg g$^{-1}$ min$^{-1}$) is the initial adsorption rate.

2.4. Leaching Test

The leaching tests of Fe ions from IOMgO at different pH were conducted to evaluate the stability of IOMgO. 0.2 g of IOMgO was dispersed in 100 ml aqueous solution with a pH ranging from 2.0 to 10.0 and agitated at 250 rpm for 5 h. The leached concentration of Fe in the solution was determined by ICP.

3. RESULTS AND DISCUSSION

3.1. Material Characterization

The FE-SEM images in Figure 1 show that the morphology of the natural IO was not changed by coating with MgO. Images of the surface of both IO and IOMgO taken at 100 k times magnification, presented similarly countless nanoparticles ranging from 45 to 250 nm (Figs. 1(C) and (G)). This phenomenon agreed well with the findings of Lemine and Rivas et al., delineating that larger (50–200 nm) IO particles were the agglomerates of smaller (2–14 nm) particles due to their magnetic property. Since the morphologies of IO and IOMgO were not differentiated, elemental mapping was conducted to observe the distribution of elements on the surface of IO (Fig. 1(B)) and IOMgO (Fig. 1(F)). Elemental mapping revealed that Si and Al existed on the surface of IO along with the core element, Fe. As shown in other studies on IO, SiO$_2$ (3.3±15.6%) and Al$_2$O$_3$ (1.4±13.0%) were found at different concentrations depending on the size and the location of the IO samples being retrieved. Elemental mapping also indicated that the positions of Si and Al on the IO were of a similar pattern. Interestingly, the mapping analysis of IOMgO showed that Mg was homogeneously dispersed on the sites analogous to Si and Al. The EDS results (Fig. 1(D)) revealed that the weight percentages of Si (9%) and Al (8.2%) on IO were reduced to 4.3% and 5%, respectively, on IOMgO, and 3.5% Mg was additionally shown. Therefore, based on the results of elemental mapping and EDS, it can be inferred that MgO was coated on the surface of either SiO$_2$ or Al$_2$O$_3$. Since the exact phase of Mg was still unidentified, XRD analysis was conducted.

The HR-TEM image of IO in Figure 2 displayed two different lattice fringes of 0.21 and 0.25 nm, identifying MgO and Fe$_3$O$_4$, respectively. This explains that MgO was coated on SiO$_2$ or Al$_2$O$_3$ as an outer-layer crystallized form.

In order to find out the surface characteristics of IO and IOMgO, the surface analysis and MgO content measurement were conducted via N$_2$ gas isotherm, XRF and aqua regia extraction. As a result, the BET surface area (15.1 m$^2$ g$^{-1}$) of IO in this study was similar to those of other references (10–13.1 m$^2$ g$^{-1}$). Observing the FE-SEM images, the surface area measured might be created by the rough surface of agglomeration between nano-particles. However, when MgO was coated, the BET surface area decreased to 12.1 m$^2$ g$^{-1}$.

Figure 3 shows the XRD patterns of IO and IOMgO. IO exhibited sharp XRD diffraction peaks which can be assigned to crystallized minerals such as hematite (Fe$_2$O$_3$, PDF: 00-033-0664), magnetite (PDF: 01-076-0957), and iron silicate oxide (FeSiO$_3$, PDF: 01-089-6228). For the case of Fe$_3$O$_4$, similar peak diffraction was found by Lemine who analyzed commercial nanocrystalline Fe$_3$O$_4$. Although Al was detected with SEM-EDS and XRF, it was not identified by XRD so that can infer that Al has an amorphous phase. When compared to the peak pattern of IO, the intensities of FeSiO$_3$ peaks were reduced and a new set of peaks of a new mineral phase, dimagnesium silicate (Mg$_5$O$_7$Si), was shown on IOMgO. As an important aspect, it can explain that the major phase (FeSiO$_3$) of IO was replaced with Mg$_5$O$_7$Si (PDF: 01-078-1982) by the coating of Mg on IO. The results of XRF discovered that SiO$_2$ (0.28 mmol g$^{-1}$) and MgO (0.37 mmol g$^{-1}$) existed on IOMgO, corresponding to 16.9 and 14.9 mg g$^{-1}$, respectively. Based on the XRF result, the molar ratio of SiO$_2$ to MgO was 1:1.3. Similar to XRF, the content of MgO measured by aqua-regia extraction was found to be 10.3–11.1 mg g$^{-1}$. Compared to the value from XRF, these values might be reasonable, since aqua regia extraction only gave 70–90% recovery of metals. Based on the elemental mapping images, XRF and XRD analysis, it can be strongly inferred that Mg was linked mainly to the Si on the IO surface, forming a functional group (Mg$_5$O$_7$Si).

3.2. Adsorption Isotherms and Kinetics

Figure 4(A) shows the Pb adsorption isotherms of IO and IO\textsuperscript{MgO}. IO\textsuperscript{MgO} had a sharp increase in adsorption capacity between 30 and 60 mg L\textsuperscript{−1} of Pb concentration due to complete 100% removal of Pb. At 90, 120 and 150 mg L\textsuperscript{−1} of initial Pb concentration, \(C_{eq}\) increased to 25, 55, and 85 mg L\textsuperscript{−1}, respectively, while \(Q_{eq}\) values were 31–32 mg g\textsuperscript{−1}. This indicates that IO\textsuperscript{MgO} reached a saturated sorption capacity.

The equilibrium data for Pb adsorption on IO and IO\textsuperscript{MgO} were fitted to Langmuir and Freundlich equations. The model parameters and their determination coefficients (\(R^2\))
were obtained and listed in Table I. Other inorganic materials used for the removal of Pb were also included in the table to be compared with IO\textsuperscript{MgO}. When $R^2$ values were compared, the Langmuir model fit more accurately than the Freundlich model. This indicates that Pb was dominantly removed by homogeneous sorption functional groups and chemical reaction.

By the Langmuir isotherm model, the maximum adsorption capacities ($Q_{\text{max}}$) of IO and IO\textsuperscript{MgO} were 4.6 and 33.9 mg g\textsuperscript{-1}, while the Langmuir equilibrium constants ($K_L$) were 0.66 and 1.69, respectively. The $Q_{\text{max}}$ of IO\textsuperscript{MgO} was 7.4 times higher than that of IO. This clearly indicates that the MgO on the surface of IO was the major factor for the removal of Pb. Due to that, the Pb adsorption capacity based on the MgO content was calculated through subtracting $Q_{\text{max}}$ of IO from $Q_{\text{max}}$ of IO\textsuperscript{MgO} (Fig. 4(B)). As a result, it was found to be 2,724 mg of Pb (g of MgO)$^{-1}$. This value was much higher than the Pb sorption capacity (1,980 mg g\textsuperscript{-1}) of flowerlike magnesium oxide nanostructures reported by Cao et al.\textsuperscript{2}

In general, the adsorption affinity of Pb increases as the value of $K_L$ increases. Except for pretreated clinoptilolite\textsuperscript{34} and manganese oxide coated carbon nanotubes,\textsuperscript{35} IO\textsuperscript{MgO} had a relatively higher $K_L$ and maximum sorption capacity than other media. Based on further analysis of the Langmuir equation, the dimensionless parameter of the equilibrium or adsorption intensity ($R_L$) can be expressed by

$$RL = \frac{1}{1 + K_L C_0}$$

where $C_0$ (mg L\textsuperscript{-1}) is the initial amount of adsorbate. The $R_L$ parameter is considered as a more reliable indicator of the adsorption. There are 4 probabilities for the $R_L$ value:

1. $0 < R_L < 1$ for favorable adsorption,
2. $R_L > 1$ for unfavorable adsorption,
3. $R_L = 1$ for a linear adsorption isotherm and
4. $R_L = 0$ for irreversible adsorption.\textsuperscript{36, 37}

Figure 2. HR-TEM image of IO\textsuperscript{MgO} (the lattice fringes of 0.21 and 0.25 nm were identified as MgO and Fe\textsubscript{2}O\textsubscript{3}, respectively).

Figure 3. XRD patterns of IO and IO\textsuperscript{MgO}.

Figure 4. Pb adsorption (A) isotherms of IO and IO\textsuperscript{MgO} (fit lines were obtained using Langmuir isotherm model) and (B) isotherms of IO\textsuperscript{MgO} based on MgO content [mg Pb (g of MgO)$^{-1}$]. (C) kinetics of IO and IO\textsuperscript{MgO} (fit lines were obtained using the pseudo second order kinetic model).
The $R_1$ value ranges from 0.004 to 0.019 between 30 and 150 mg L$^{-1}$ and approaches zero with the increase of $C_0$ value. This parameter ($0 < R_1 < 1$) indicated that the IO$^{MgO}$ is a suitable adsorbent for the adsorption of Pb from an aqueous solution.

Meanwhile, the Freundlich parameters also designate whether the nature of adsorption is favorable or unfavorable. As a function of adsorption strength, the value of 1/n, for IO$^{MgO}$ was 0.11, which is smaller than 1. This indicates that the value represents a convex, curved downward, Langmuir-type isotherm, where the marginal sorption energy decreases with the increase of surface concentration.

Table I. Comparison of Langmuir and Freundlich isotherm models between IO$^{MgO}$ and other inorganic materials for the removal of Pb.

<table>
<thead>
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<th>Media</th>
<th>Langmuir</th>
<th>Freundlich</th>
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<tbody>
<tr>
<td></td>
<td>$K_L$ (L mg$^{-1}$)</td>
<td>$Q_{max}$ (mg g$^{-1}$)</td>
</tr>
<tr>
<td>Hydroxyapatite/magnetite composite$^{44}$</td>
<td>0.17</td>
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<tr>
<td>Calcite$^{45}$</td>
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<td>Turkish kaolinite clay$^{46}$</td>
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<tr>
<td>Iron-oxide-coated-crushed brick$^{48}$</td>
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<tr>
<td>Pretreated clinoptilolite$^{49}$</td>
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<tr>
<td>Manganese oxide-coated Bentonite$^{49}$</td>
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<td>58.9</td>
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<tr>
<td>Manganese oxide coated carbon nanotubes$^{50}$</td>
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<td>78.7</td>
</tr>
<tr>
<td>IO$^{MgO}$ (this study)</td>
<td>1.69</td>
<td>33.9</td>
</tr>
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</table>

3.3. Mechanism of Pb Removal

A set of kinetic tests, SEM-EDS and XRD of IO$^{MgO-Pb}$ were conducted to elucidate the mechanism of Pb removal by IO$^{MgO}$. In the kinetic tests, the concentrations of Mg released and Pb removed were identified. It was found that the concentration of released Mg increased with an increase of Pb removal, indicating that Mg was substituted by Pb during adsorption (Fig. 5). When all data used in the kinetic study had a linear relationship, the molar ratio of Mg released to Pb adsorbed was found to be 0.74. Meanwhile, Cao et al. reported the equivalent molar ratio between the released Mg and adsorbed Pb for flowerlike magnesium oxide nanostructures.$^{51}$ For the case of flowerlike MgO, the functional group is only MgO. But, the main functional group of IO$^{MgO}$ for the removal of Pb is Mg$_2$O$_3$Si. This might be the main reason for the difference in the substitution behaviors in contrast with flowerlike MgO.

The FE-SEM image (Fig. 6(A)) shows that white precipitates were dispersed on the surface of IO$^{MgO-Pb}$. The 100 k-times magnified image (Fig. 6(B)), presents similarly countless nanoparticles ranging from 45 to 250 nm agglomerated together. Elemental mapping was also conducted to identify elements on white precipitates.
Figure 6. (A) FE-SEM images of IO\(^{MgO}\)-Pb, (B) \( \times 100 \) k time magnification image, (C) elemental mapping analysis of IO\(^{MgO}\)-Pb, SEM images and chemical compositions of (D) IO, (E) IO\(^{MgO}\) and (F) IO\(^{MgO-Pb}\), (G) EDS analysis of white precipitate of IO\(^{MgO-Pb}\), and (H) XRD pattern of IO\(^{MgO-Pb}\).

(Fig. 6(C)). When the FE-SEM image and elemental mapping were compared, the locations of white precipitates exactly matched to Pb. Besides that, Figures 6(D), (E) and (F) show the weight percentages of Fe, Pb, Al, Si and Mg for IO, IO\(^{MgO}\) and IO\(^{MgO-Pb}\), respectively. Figure 6(F) demonstrates that a high weight percentage of Pb (30.3%) was found on the white precipitate while the non-white location had a low Pb content (1.53%). The precipitates containing high Pb had higher amount of Si (3.15%) compared to the low Pb site (2%), explaining that the Pb was non-homogenously precipitated due to the heterogeneous location of functional group, Mg\(_2\)O\(_4\)Si. For the same reason, the study conducted by Suzuki et al. also revealed that Pb were heterogeneously precipitated on MgO based kaolinite.\(^{39}\)

In this study, two possible mechanisms of Pb removal by IO\(^{MgO}\) could be proposed: substitution/precipitation and surface complexation.

Substitution and precipitation:

\[
\text{Si} - \text{O} - \text{Mg} - \text{OH} + \text{Pb}^{2+} \rightarrow \text{Si} - \text{O} - \text{PbOH} + \text{Mg}^{2+}
\]

Surface complexation:

\[
\text{Fe} - \text{OH} + \text{Pb}^{2+} \rightarrow \text{Fe} - \text{O} - \text{Pb} + \text{H}^+
\]

The EDS analysis shows that the Mg weight percentage (3.57%) of IO\(^{MgO}\) reduced to 1.32% after the Pb adsorption. Thus, when the weight percentages of Mg released (0.09 mole) and Pb removed (0.146 mole) were recalculated to molar basis, it was found to be 0.62, which is similar to the value with kinetic data shown at Figure 5. Whiles, the weight percentages of Fe and Si on the non-white location were 56.4 % and 2%, respectively, which resulted in molar ratio of 1:0.07. This indicates that the Fe\(_2\)O\(_3\) dominantly exist compared to FeSiO\(_3\). And, the weight percentage of Pb was 1.53% (0.007 mole) so that the Pb removal by Fe\(_2\)O\(_3\) was a much smaller fraction. Figure 6(H) shows the XRD pattern of IO\(^{MgO-Pb}\). The IO\(^{MgO-Pb}\) media was obtained after the Pb adsorption test that was conducted for 24 hours using 60 mg L\(^{-1}\) Pb and 0.2 g IO\(^{MgO}\). The sample was then dried in air for 24 hours prior to XRD analysis. For the case of XRD pattern of IO\(^{MgO}\), the Mg\(_2\)O\(_4\)Si and FeSiO\(_3\) peaks were of equal intensities. However, the Mg\(_2\)O\(_4\)Si peak intensity was comparably reduced at IO\(^{MgO-Pb}\), indicating that Mg\(_2\)O\(_4\)Si was used for Pb removal. Besides that, IO\(^{MgO-Pb}\) had 2 additional peaks at 27° and 34° of 2\(\theta\), which were identified as plumbophyllite (Pb\(_2\)Si\(_4\)O\(_{10}\)·H\(_2\)O, ICSD collection code, 164669). Interestingly, the calculated molar ratio between existed SiO\(_2\) (0.28 mmol g\(^{-1}\)) and removed Pb (0.14 mmol g\(^{-1}\)) was 2:1 which is exactly plumbophyllite (Pb\(_2\)Si\(_4\)O\(_{10}\)·H\(_2\)O). Overall, it is deduced that substitution and precipitation is dominant mechanism for Pb removal by IO\(^{MgO}\).

3.4. Magnetic Separation of IO\(^{MgO-Pb}\)

Magnetic measurements were performed for IO, IO\(^{MgO}\) and IO\(^{MgO-Pb}\) samples (Fig. 7) using an AGM. The uncoated, natural IO had the highest value of magnetization saturation (Ms, 29.29 emu g\(^{-1}\)) compared to IO\(^{MgO}\)
leaching test on aqueous solutions at different pH levels to evaluate the leaching possibilities of IOMgO. Figure 8 shows that the concentration of leached Fe is negligible at pH 4 to 9 because it is below the regulation level which is 1 mg L$^{-1}$. At a pH level of 2, the leaching of Fe was up to 5.5 mg L$^{-1}$. A similar trend has been noticed for magnetite loaded multi-wall carbon nanotubes, in which Fe leaching was 11.7 mg L$^{-1}$ at pH 2.$^{13}$

4. CONCLUSIONS
In this study, IOMgO was prepared by a rapid and fast synthesis route using non-toxic, environmentally benign chemicals. The removal capability of Pb based on MgO amount of IOMgO was 2,724 mg Pb (g MgO)$^{-1}$, which was higher than that (1,980 mg g$^{-1}$) of flowerlike MgO nanostructures reported by Cao et al. When isotherm and kinetics results of IOMgO were compared with other inorganic materials, IOMgO had a higher Langmuir constant and maximum sorption capacity for lead (Pb). The kinetics, FE-SEM, elemental mapping and XRD results indicated that the mechanism for the removal of Pb by IOMgO was substitution followed by precipitation between Mg and Pb. Since the basic material, IO, is cheap and easily available in abundance, mass production of IOMgO is applicable for the treatment of wastewater containing heavy metals by use of simple and fast magnetic separation.

Acknowledgments: This work was supported by an Exploratory Research Grant Scheme (ERGS) grant funded by the government of Malaysia (MOHE), No. ER009-2013A.

References and Notes

Figure 7. (A) Hysteresis loops of IO, IOMgO, and IOMgO-Pb. (B) Separation image of IOMgO-Pb using an external permanent magnet.

Figure 8. Leached Fe concentration of IOMgO at different pH levels.

Figure 9. Kinetics results of IOMgO were compared with other inorganic materials, IOMgO had a higher Langmuir constant and maximum sorption capacity for lead (Pb). The kinetics, FE-SEM, elemental mapping and XRD results indicated that the mechanism for the removal of Pb by IOMgO was substitution followed by precipitation between Mg and Pb. Since the basic material, IO, is cheap and easily available in abundance, mass production of IOMgO is applicable for the treatment of wastewater containing heavy metals by use of simple and fast magnetic separation.

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