Research paper

Electrochemical purification of kaolinitic for removing Fe and Ti oxides applying an ultrasonic pre-treatment

Melo-López A.A.¹, Veloz-Rodríguez M.A.¹, Reyes-Cruz V.E.², Urbano-Reyes G.², Cobos-Murcia J.A.¹,², Legorreta-García F.²

¹Universidad Autónoma del Estado de Hidalgo, Área Académica de Ciencias de la Tierra y Materiales, Carr. Pachuca-Tulancingo Km 4.5 s/n, Mineral de la Reforma, Hidalgo C.P. 42184, Mexico
²Consejo Nacional de Ciencia y Tecnología, Departamento de Cátedras, Av. Insurgentes Sur 1582, Col. Crédito Constructor, Deleg. Benito Juárez, México D.F. C.P. 03940, Mexico

ARTICLE INFO

Keywords:
Kaolinitic clay purification
Ultrasonic pre-treatment
Electrochemical purification
Fe and Ti oxides

ABSTRACT

A study to determine the mechanisms of electrochemical purification and the effect of ultrasonic pre-treatment to remove impurities of Fe and Ti oxides was presented with the intention of optimizing the purification process of kaolinitic clays and increasing their use in different industrial applications. Cyclic voltammetry and chronocomamperometry studies as well as SEM/EDS, ICP and whiteness index (WI) were conducted to evaluate the electrochemical purification of four different kaolinitic clays (ACE, CFL, ASC and AAM), with and without ultrasonic pre-treatment. The results show that the purification of kaolinitic clays was initially carried out by the chemical dissolution of Fe and Ti oxides, with oxalic acid added and pH < 1.5, while the electrochemically progressive deposition to Fe and Ti occurs on the silver electrode. Studies indicated that there is a higher removal of the impurities of Fe and Ti (82–92% Fe and 35–79% Ti) for CFL, ASC and AAM kaolinitic clays when an ultrasonic pre-treatment was applied; whereas ACE kaolinitic clay it was indifferent to ultrasound treatment. The results can be attributed to the fact that ACE kaolin clay contains low contents of magnetite and anatase, as well as, a high quantity of kaolinite. Finally, some kaolinitic (ACE and CFL) obtained a whiteness index > 90, when ultrasonic pre-treatment was applied, thus increasing their use in different applications.

1. Introduction

Kaolinitic clays are primarily composed of kaolinite, a 1:1 clay mineral. Kaolinite consists of a tetrahedral Si sheet and an octahedral Al sheet, joined by common O atoms. The octahedral Al sheet is terminated by Al–OH groups, which are H-bonded to the O atoms of the Si sheet of the next kaolinite layer (Bergaya and Lagaly, 2013; Bartolomé, 1997). Nowadays, kaolinites are one of the most used minerals in the industry due to their versatility and great number of applications, for instance in ceramics, paper, cement, paints, pesticides, pharmaceuticals and the cosmetics industry (Wilson, 2007; Saikia et al., 2003).

This is the reason why there is a significant demand for kaolinitic clays as a raw material and it is increasing day by day. However, few suppliers can deliver the quality characteristics since the deposits are contaminated with impurities that reduce the desirable properties for the industry. The required quality specifications are very strict, both in purity and in colour; white kaolinitic clay is considered first in terms of quality, the cream colour second and the reddish third. For example, kaolin specifications for paper coating require kaolinite from 90 to 100%, < 0.5–1.8 mass% Fe₂O₃ and TiO₂ (0.4–1.6%) and a whiteness above 85. In the ceramic grade, a kaolinite content of 75 to 85 mass %, < 0.9% of Fe₂O₃ and a whiteness of at least 80 are required (PMC, 2014).

The presence of these associated minerals (non-kaolinitic clay constituents) in natural kaolinitic clay deposits also reduces the commercial value of this material. Some of the main contaminants are (hydr) oxides of Fe and Ti (Ambikadevi and Lalithambika, 2000), its elimination being one of the first problems that needs to be solved for the material to be beneficial to producers and to this industrial sector. Thus, a great deal of effort has been devoted on purifying kaolinitic clays to use as a raw material in a great number of applications.

Nowadays, the purification of kaolinitic clays is carried out by the elimination of (hydr)oxides of ferrous, magnesium, titanium and other metallic oxides by leaching, flotation, flocculation and high-intensity magnetic separation (Bergaya and Lagaly, 2013; Ambikadevi and Lalithambika, 2000; Aghaie et al., 2009; Baba et al., 2016; Cao et al.,...
2. Materials and methods

2.1. Preparation and characterization of kaolinitic clays

Samples of kaolinitic clays used in this work were named according to the places where they were collected or the colours they presented. The samples were: a kaolinitic clay from Escondida (ACE), a kaolinitic clay from Flores (CFL), a brown kaolinitic clay (AAM) and a grey kaolinitic clay (ASC) from Hidalgo State, Mexico. These samples were crushed and milled before being sieved to < 44 μm (− 325 mesh size). The results of X-ray diffraction analysis corroborated the presence of the main mineralogical species, as shown in Fig. 1 and Table 2.

2.2. Slurry preparation and ultrasonic pre-treatment

A slurry was prepared with 100 g of kaolinitic clay natural, with a 1:2 ratio of kaolinitic clay and deionized water (pulp density of 1.28 g/ml) stirred at 800 rpm for 30 min, in a glass beaker. The dispersion was allowed to stand for another 30 min before the solids that precipitated at the bottom were decanted to ensure only the solids in the slurry were used. Later, oxalic acid (H2C2O4) 1 M was added to the slurry to obtain a pH close to 1.3 and then the ultrasound pre-treatment was applied. For this treatment, the glass container with the slurry was left in an ultrasound bath for 90 min at 100 W and a frequency of 42 kHz, employing a Branson 3510 ultrasonic bath instrument.

2.3. Thermodynamic study

Equilibrium diagrams of Fe–Ti were created to ascertain the thermodynamic conditions of pH and the potential needed to carry out Fe and Ti leaching, as well as establishing the conditions needed to deposit these metals and remove them from the kaolinitic clays. Pourbaix diagrams of kaolinitic clays with a higher and lower content of Fe and Ti were constructed using the Outokumpu HSC Chemistry software for Windows. The system conditions were: a) 0.629 mM Fe, 0.037 mM Ti for AAM kaolinitic clay and b) 0.27 mM Fe, 0.095 mM Ti for ASC kaolinitic clay in aqueous medium at 25 °C.

2.4. Electrochemical studies

Electrochemical studies were performed using cyclic voltammetry, cathodic inversion voltammetry and chronoamperometry techniques with a typical three-electrode cell, connected to an instrument PAR 263A potentiostat–galvanostat. A silver plate of high purity was used as the working electrode with a dimensionally stable (DS) electrode as an auxiliary. A saturated calomel electrode (SCE, E 0 = 0.242 V vs. a standard hydrogen electrode) was used as the reference electrode in all experiments. All potential values were reported with respect to SCE. The slurry that was used as the bath in the ultrasonic pre-treatment was also used as the electrolyte in the electrochemical study at pH 1.3. Finally, kaolinitic clays that were purified electrochemically, with and without ultrasonic pre-treatment, were characterized by inductively coupled plasma (ICP) with a Perkin Elmer instrument ICP-OES Optima 8300 in order to identify its final chemical composition; in addition, the whiteness index (WI) was determined using an OceanView UV spectrometer USB4000 model.

3. Results and discussion

3.1. Characterization of kaolinitic clays

Table 1 shows the results of the ICP chemical analysis of the four kaolinitic clay samples (ACE, CFL, AAM and ASC). The AAM kaolinitic clay exhibits the highest iron content (which determines its brown coloration iron-stained) and magnesium, as well as a high amount of titanium (> 1%). The ASC kaolinitic clay also has significant amounts of iron and the highest amount of titanium, which are banned in some industrial applications such as ceramics and paper. The CFL and ACE samples show the presence of iron in a smaller but still considerable quantity (> 2%), which prevents its use in some industrial applications. The results of X-ray diffraction analysis corroborated the presence of the main mineralogical species, as shown in Fig. 1 and Table 2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>% wt</th>
<th>Al</th>
<th>Zr</th>
<th>Fe</th>
<th>Mg</th>
<th>Ti</th>
<th>Ca</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>29.397</td>
<td>0.038</td>
<td>3.573</td>
<td>0</td>
<td>0.558</td>
<td>0.012</td>
<td>56.819</td>
<td></td>
</tr>
<tr>
<td>CFL</td>
<td>23.648</td>
<td>0.076</td>
<td>2.277</td>
<td>0</td>
<td>0.078</td>
<td>0</td>
<td>52.815</td>
<td></td>
</tr>
<tr>
<td>AAM</td>
<td>19.457</td>
<td>0.034</td>
<td>21.515</td>
<td>0.711</td>
<td>1.253</td>
<td>0</td>
<td>54.680</td>
<td></td>
</tr>
<tr>
<td>ASC</td>
<td>22.301</td>
<td>0.074</td>
<td>8.053</td>
<td>0.163</td>
<td>3.255</td>
<td>0.393</td>
<td>46.011</td>
<td></td>
</tr>
</tbody>
</table>
Kaolinite (JCPDF 089–6538), silica in the form of alpha quartz (JCPDF 089–8937), an amorphous phase of quartz (JCPDF 086–1561) and cristobalite (JCPDF 076–0939), are the main constituents. The iron is considered as an impurity and is present as magnetite (JCPDF 086–1355, 086–1341) or lepidocrocite (JCPDF 076–2301) and the titanium oxide as anatase (JCPDF 071–1166), as well as a small amounts of a potassium aluminium-silicate specie (JCPDF 31–0965) in the kaolinitic clay AAM (< 0.6%). From the analysis of the diffraction patterns the values of crystallinity index (HI and AGFI) were determined in order to give info about hard or soft kaolin types (see Table 2) according their crystallinity. Murray and Lyons (1960) revealed a correlation between the total amount of Fe2O3 and TiO2 and the degree of crystallinity, where the well-crystallized kaolins contained the smallest quantity of these two oxides, and the poorly crystallized kaolins contained the largest amount. According to Hu and Liu (2003), the kaolinite in soft kaolin corresponds to well-ordered kaolinite, whereas in the hard kaolins it correspond to poorly ordered kaolinite. Kaolinite is considered to be well ordered if its Hinckley index (HI) > 0.9 (Hinckley, 1963; Aparicio and Galan, 1999) or Aparicio-Galan-Ferrell Kaolinite index (AGFI) > 1.25 in low-defect kaolinite.

Table 2
Mineralogical composition (% wt), crystallinity index of the kaolinite and hard or soft kaolin type.

<table>
<thead>
<tr>
<th>Kaolinitic clay</th>
<th>Kaolinite (Al2Si2O5(OH)4)</th>
<th>Quartz (SiO2)</th>
<th>Cristobalite (SiO2)</th>
<th>Magnetite (Fe3O4)</th>
<th>Anatase (TiO2)</th>
<th>Lepidocrocite (γ-FeO(OH))</th>
<th>Crystallinity index</th>
<th>Kaolin type</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>62.3</td>
<td>22.4</td>
<td>14.1</td>
<td>0.8</td>
<td>0.4</td>
<td>0</td>
<td>1.1</td>
<td>1.33</td>
</tr>
<tr>
<td>CFL</td>
<td>43.6</td>
<td>32.8</td>
<td>20.0</td>
<td>2.6</td>
<td>1.0</td>
<td>0</td>
<td>1.69</td>
<td>1.64</td>
</tr>
<tr>
<td>AAM</td>
<td>21.6</td>
<td>71.5</td>
<td>0.0</td>
<td>3.6</td>
<td>2.5</td>
<td>0.8</td>
<td>0.85</td>
<td>0.95</td>
</tr>
<tr>
<td>ASC</td>
<td>28.3</td>
<td>62.9</td>
<td>0.0</td>
<td>2.0</td>
<td>6.8</td>
<td>0</td>
<td>0.77</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Fig. 1. XRD patterns obtained on samples of the different kaolinitic clays: ACE, CFL, AAM and ASC.
potential range from $-1$ to $1.5$ and at a potential range of $-0.755$ V to $1.755$ V. With the intention of confirming the results obtained in the thermodynamic study, an electrochemical study involving iron and titanium leaching on the ACE, AAM and ASC kaolinitic clays took place, both without (i) and with (ii) the ultrasonic pre-treatment.

3.3. Electrochemical study

Fig. 3(a–d) shows the cyclic voltammograms obtained with ACE, CFL, AAM and ASC kaolinitic clays, respectively, without (i) and with (ii) the ultrasonic pre-treatment. The scan began in the cathodic direction from the open-circuit potential ($-0.05$ V) at a sweep rate of 25 mVs$^{-1}$ and between potentials of $-1$ to $1300$ mV. For all the Fig. 3 (a–b), two reduction processes were observed (R1 and R2) both without and with ultrasonic pre-treatment. These processes have already been characterized and were associated with the reduction of some species of iron and titanium from the kaolinitic clays (Melo et al., 2014; Flores et al., 2017). In terms of the anodic potentials, a scarcely visible oxidation process O1 (see an inset in Fig. 3a–d) was observed in all the kaolinitic clays under study both without and with the ultrasonic pre-treatment. This peak was assigned to oxidation of Fe and Ti previously deposited on the electrode (Melo et al., 2014).

It is important to note that the ACE clay response without the ultrasonic pre-treatment (curve i) shows a higher current density during the oxidation process O1 than with the pre-treatment (curve ii) (see an inset in Fig. 3a). Meanwhile, without ultrasonic pre-treatment (curve i) the CFL, AAM and ASC kaolinitic clays show lower current density than the samples pre-treated with the ultrasonic process (curve ii) (see an inset in Fig. 3b–d). This behaviour was attributed to the layers of the crystalline structure from ACE kaolinitic clay not having a greater resistance for releasing species of Fe and Ti, while in the other kaolinitic clays (CFL, AAM and ASC) the ultrasonic pre-treatment is necessary to facilitate the diffusion of Fe and Ti species.

In order to corroborate these facts the ultrasonic pre-treatment on the quantity of Fe and Ti removed from the kaolinitic clays, was studied with a cathodic potential by chronoamperometry. Fig. 4 shows potentiostatic transient responses obtained for each of the four kaolinitic clays (ACE, CFL, AAM and ASC) when a potential of $-1300$ mV was imposed for 3600 s, both without and with the ultrasonic pre-treatment. The responses show a typical exponential drop in current during the capacitive processes, which is associated with the adsorption and polarization of the species on the electrode surface at short times. Moreover, the characteristic behaviour of the metal nucleation with the increase in faradaic current and the presence of a maximum was evident (Soto et al., 1996).

The ACE kaolinitic clay (Fig. 4a) was the only one with a lower reduction current with the pre-treatment (curve ii) than without the ultrasonic pre-treatment (curve i) during the entire electrolysis process, which had already been observed in the voltammetry study. Meanwhile, for the CFL, AAM and ASC kaolinitic clays (Fig. 4b–d and) it was observed that the reduction current of the species is higher with the pre-treatment (curve ii) than the current obtained from the samples without the ultrasonic pre-treatment (curve i). These results indicate that it is probable that there is a higher amount of Fe and Ti impurities that have been removed from the CFL, AAM and ASC kaolinitic clays with the pre-treatment (curve ii) than without the ultrasonic pre-treatment (curve i), with the exception of the ACE kaolinitic clay. These findings are in agreement with the results of the voltammetry studies.

Table 3 presents the results of the final chemical analysis by ICP of Fe and Ti (% in weight) remaining in the four kaolinitic clays, as well as the percentage of Fe and Ti removed from the four kaolinitic clays after electrochemical purification, both without and with the ultrasonic pre-
The data shows that a significant amount of Fe has been removed from the kaolinitic clays via electrochemical leaching in percentages of 52 to 84% without the ultrasonic pre-treatment, while with the ultrasonic pre-treatment these percentages ranged from 82 to 92% (see Table 3). It is evident that a final composition of Fe < 1% was achieved only for the ACE and CFL kaolinitic clays when ultrasound was applied. Meanwhile, for the AAM and ASC kaolinitic clays, the final Fe content remains high, although its elimination is considerable, especially when ultrasound is applied.

In Table 3, it is noted that titanium has also been removed from the four kaolinitic clays (although not in the same proportion as iron) up to a content below 1% following the application of the ultrasonic pre-treatment. However, when ultrasonic pre-treatment was not applied, the amount of titanium remaining is above 1% in some kaolinitic clays (AAM and ASC). These findings indicate that the effect of the ultrasonic pre-treatment has enhanced the amount of iron and titanium removed from the kaolinitic clays in comparison to the kaolinitic clays studied without the ultrasonic pre-treatment. This is because ultrasound promotes diffusive processes, increasing mass transport (metal ions to the cathode) and probably a greater dispersion of particles that allows better exposure of the impurities to electrochemical treatment. However, in ACE kaolinitic clay the effect was not the same, probably due to the fact that ACE contains low contents of impurities as magnetite and anatase, as well as, high quantities of kaolinite.

The proposed reaction mechanisms for the electrochemical purification of the kaolinitic clays are as follows:

To remove hematite:

$$\text{Fe}_2\text{O}_3 + 3\text{H}_2\text{C}_2\text{O}_4 \rightarrow \text{Fe}_2(\text{C}_2\text{O}_4)_3 + 3\text{H}_2\text{O}$$  

$$\text{Fe}_2(\text{C}_2\text{O}_4)_3 + 6\text{e}^- \rightarrow 2\text{Fe}^0 + 3\text{C}_2\text{O}_4^{2-}$$  

To remove magnetite:

$$4\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{C}_2\text{O}_4 \rightarrow 4\text{Fe}_2(\text{C}_2\text{O}_4)_3 + 4\text{C}_2\text{O}_4 + 4\text{H}_2\text{O}$$  

$$\text{Fe}_2(\text{C}_2\text{O}_4)_3 + 6\text{e}^- \rightarrow 2\text{Fe}^0 + 3\text{C}_2\text{O}_4^{2-}$$  

$$\text{Fe}(\text{C}_2\text{O}_4)_2 + 2\text{e}^- \rightarrow \text{Fe}^0 + 2\text{C}_2\text{O}_4^{2-}$$

To remove ulvospinel:

$$\text{Fe}_2\text{Ti}_2\text{O}_5 + 4\text{H}_2\text{C}_2\text{O}_4 \rightarrow \text{Fe}_2(\text{C}_2\text{O}_4)_3 + 2\text{Ti}(\text{C}_2\text{O}_4)_3 + 4\text{H}_2\text{O}$$  

$$\text{Fe}_2(\text{C}_2\text{O}_4)_3 + 6\text{e}^- \rightarrow 2\text{Fe}^0 + 3\text{C}_2\text{O}_4^{2-}$$  

$$\text{Ti}(\text{C}_2\text{O}_4)_2 + 2\text{e}^- \rightarrow \text{Ti}^0 + 2\text{C}_2\text{O}_4^{2-}$$

To remove rutile or anatase:

$$\text{TiO}_2 + 2\text{H}_2\text{C}_2\text{O}_4 \rightarrow \text{Ti}(\text{C}_2\text{O}_4)_2 + 2\text{H}_2\text{O}$$  

$$\text{Ti}(\text{C}_2\text{O}_4)_2 + 4\text{e}^- \rightarrow \text{Ti}^0 + 2\text{C}_2\text{O}_4^{2-}$$

The mechanisms begin with a chemical dissolution of Fe and Ti...
oxides with the oxalic acid (reactions 1a, 2a, 3a and 4a), generating oxalate complexes species in solution with the oxalate ion. These species are then progressively reduced to Fe and Ti metals on the silver electrode via an electrochemical reaction (reactions 1–4 b or c) by the imposition of a cathodic current.

Fig. 5 shows an analysis by scanning electron microscopy of the deposits obtained on the cathode electrode, where a three-dimensional growth of the deposits and the presence of cubic crystals was observed (Fig. 5a). This is in accordance with was mentioned above. Potentiostatic transient responses had characteristic behaviour of metal nucleation with the increase in a faradaic current and the presence of a maximum. In the spectrum obtained by EDS on the deposited crystals (Fig. 5b), the presence of Fe and Ti was evident. The presence of silver (Ag) observed in the EDS spectrum was due to the Ag cathode.

Table 3 shows the results of the whiteness index (WI) obtained by an OceanView UV spectrometer model USB4000 and the OceanView 1.4 software in two of the four kaolinitic clays, following the application of an electrochemical purification without and with the ultrasonic pre-treatment. The data demonstrate that WI obtained for ACE and CFL kaolinitic clays was > 90 with the ultrasonic pre-treatment, while without the ultrasonic pre-treatment (although the whiteness is an improvement) the WI was slightly < 90. That is, an increase in WI values of > 20 points was observed in these two kaolinitic clays when an application of an electrochemical purification with the ultrasonic pre-treatment, with respect to the initial WI values. For the AAM and ASC kaolinitic clays, the whiteness degree achieved was slightly below 80 WI after electrochemical and the ultrasonic pre-treatment, from an initial value of < 50 WI. This is understandable because these two last kaolinitic clays have a greater amount of Fe and Ti impurities, also considered poorly ordered kaolinites or hard kaolins (see Table 2). An analysis of mineralogy and crystallinity of kaolinitic clays AAM and ASC after electrochemical and the ultrasonic pre-treatment (not shown here), indicated that mineralogical species of iron and titanium (magnetite or anatase) decreased. However, the value of crystallinity index (HI or AGFI) although slightly has been increased does not reach a value to pass from hard kaolin to soft kaolin, probably

![Fig. 4. Potentiostatic transients obtained from several kaolinitic clays: a)ACE, CFL b), AAM c) and ASC d) in solution with oxalic acid at pH 1.3 by imposing a potential of −1.4 for 3600 s without (i) and with (ii) the ultrasonic pre-treatment.](image)

### Table 3

<table>
<thead>
<tr>
<th>Sample</th>
<th>Without ultrasound</th>
<th>With ultrasound</th>
<th>Without ultrasound</th>
<th>With ultrasound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Fe (wt)</td>
<td>% Fe removed</td>
<td>% Ti (wt)</td>
<td>% Ti removed</td>
</tr>
<tr>
<td>ACE</td>
<td>0.61</td>
<td>0.63</td>
<td>0.31</td>
<td>0.32</td>
</tr>
<tr>
<td>CFL</td>
<td>1.09</td>
<td>0.25</td>
<td>0.55</td>
<td>0.31</td>
</tr>
<tr>
<td>AAM</td>
<td>3.52</td>
<td>1.69</td>
<td>1.09</td>
<td>0.82</td>
</tr>
<tr>
<td>ASC</td>
<td>2.49</td>
<td>1.15</td>
<td>2.76</td>
<td>0.68</td>
</tr>
</tbody>
</table>
because there is still high amounts of iron and titanium impurities in these clays.

Finally, these findings indicates that the increase in the WI obtained in the ACE and CFL kaolinitic clays after electrochemical purification and pre-treatment with ultrasound, expands their use in different applications of the industry (i.e. paper, ceramics, paints, pharmaceuticals, etc.). Meanwhile, AAM and ASC kaolinitic clays could only be used in applications where the required quality specifications are less stringent. Thus, these results confirms that the electrochemical purification and the ultrasonic pre-treatment applied to the kaolinitic clays show their suitability to remove Fe and Ti impurities.

4. Conclusions

The results indicated that purification of kaolinitic clays was initially carried out by the chemical dissolution mechanism of Fe and Ti oxides, which was achieved by using a sufficiently low acid pH (< 1.5) with oxalic acid. Subsequently, oxide complexes of Fe and Ti were electrochemically reduced to Fe and Ti metals on the Ag electrode. Voltammetry and chronoamperometry responses indicated that there is a higher removal of the impurities of Fe and Ti oxides for CFL, ASC and AAM kaolinitic clays when the ultrasonic pre-treatment was applied, while for ACE kaolinitic clay the use of an ultrasonic pre-treatment was irrelevant. The analyses by SEM/EDS, ICP and whiteness index (WI) confirmed these results as the impurities of Fe and Ti were eliminated from the kaolinitic clays in an important way (82–92% Fe y 35–79% Ti), as well as an increase in the whiteness index (WI) when an ultrasonic pre-treatment was applied. Further, it was determined that some kaolinitic clays (ACE and CFL) obtained a degree of whiteness > 90 WI when the ultrasonic pre-treatment was employed, which will expand their use in different applications. Finally, these results confirm that the electrochemical purification and the ultrasonic pre-treatment applied to the kaolinitic clays show their suitability in terms of removing Fe and Ti impurities.

Acknowledgements

This work was financially supported by Universidad Autónoma del Estado de Hidalgo (PIFI program). The authors wish to thank the technical support of Verónica García and Juan Hernández on the ICP and EDS studies. The authors also would like acknowledges the economic support of National Council of Science and Technology for the doctoral fellowship and to the Cátedras CONACYT program.

Conflicts of interest

The authors declare no conflict of interest.

References

