

# Dissolution behavior and dissolution mechanism of palygorskite in HCl solution<sup>\*</sup>

CAI Yuanfeng and XUE Jiyue<sup>\*\*</sup>

(Department of Earth Sciences, Nanjing University, Nanjing 210093, China)

Received June 2, 2003; revised August 1, 2003

**Abstract** The 1 mol/L, 3 mol/L and 5 mol/L HCl solutions were employed to leach two palygorskites with different trioctahedral contents in their crystal structure for different period of time. The results of the dissolution experiments show that the dissolution process could be divided into three steps, and that this dissolution behavior can be attributed to its higher  $Mg^{2+}$  content, and is restricted by the extraction behavior of  $Si^{4+}$ . The preferential extraction for  $Mg^{2+}$  promotes the extraction behavior of  $Si^{4+}$  from Si-O framework. Because the  $Si^{4+}$  in the form of amorphous  $SiO_2$  is adsorbed onto the surface of palygorskite fibre, the reaction between palygorskite and acid is obstructed. With the elapsing of time or the increasing of the acid concentration, the amorphous  $SiO_2$  flocculates, and then the channels of chemical reaction are reopened. The ratio value of  $Mg^{2+}/(Fe^{3+}+Al^{3+})$  in leaching solution tends to a fixed value, showing that the acid attacks not only the surface but also the structural channels. There are no obvious three steps observed during the acid attack on the palygorskite with a lower trioctahedral content. The differential behavior for two palygorskites is discussed.

**Keywords:** palygorskite, acid leaching, dissolution mechanism, Anhui, Mingguang, Guanshan.

Palygorskite is a kind of phyllosilicate with a fibrous morphology. Its crystal structure is built up of amphibole-like ribbons of 2:1 layer modules, but the neighbouring ribbons are mutually linked by inversion of Si-O tetrahedrons at the corner of the ribbons. This kind of linkage results in the interior channels of 0.37 nm × 0.64 nm in cross-section<sup>[1]</sup>. The external surface and the inner surface of this mineral have an efficient adsorption capacity. It is usually used as adsorbents, desiccants, decoloring agents. In order to increase the specific surface, attapulgite clay whose main mineral component is palygorskite is always activated by means of acid leaching<sup>[2~8]</sup>. The concentration of the acid is commonly controlled at about 2 mol/L<sup>[4,5]</sup>. The properties and structures may be modified for the surface of fibre and channels of activated palygorskite. The acid treatments not only increase the specific surface area of palygorskite but also increase its potential function in industrial applications. This kind of practical demand also promotes the study of acid leaching mechanism of palygorskite. Many papers have been published since the 1980s. Because of the difference in the focus of the attention, the manner, acid concentration, leaching time, and compositions of palygorskite adopted by authors, there are various opinions on the acid leaching mecha-

nism. For example, Gonzalez et al.<sup>[9]</sup> considered that acid leaching is spread all over the structural channels of palygorskite. Corma et al.<sup>[8]</sup> made a conclusion that acid leaching was processed from surface to inner of the structure and fitted for a reacting-shell model. Corma et al.<sup>[2]</sup> also carried out a short-time leaching experiment; they thought that the composition of the octahedral sheet had little effect on acid leaching. On the basis of above-mentioned results, we studied two palygorskites purified in distilled water and with different dioctahedral and trioctahedral occupancy ratios. Treated by the acid at different concentrations, and using the inductively coupled plasma quantometer (ICP-AES) the concentration of the extracted octahedral cations in leaching solution was measured. The process of extraction of cations, the changes of crystal structure, and the mechanism of acid leaching were investigated.

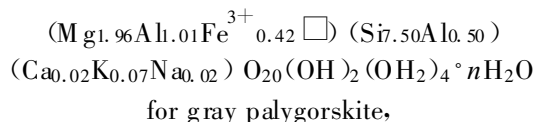
## 1 Descriptions of the samples

Two palygorskite samples were collected in Guanshan attapulgite deposits in Mingguang, Anhui Province, China. One is gray in color, and the other is pink. Their mineralogical and compositional characters have been presented in Ref. [9]. According to EPMA and  $Fe_2O_3/FeO$  ratio from wet chemical anal-

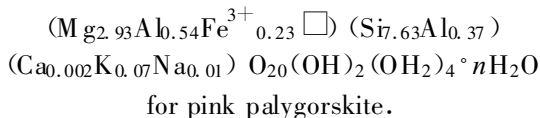
<sup>\*</sup> Supported by the National Natural Science Foundation of China (Grant No. 40172016) and the Fund for Analysis and Testing of Nanjing University

<sup>\*\*</sup> To whom correspondence should be addressed. E-mail: xuezhou@nju.edu.cn

ysis results, the structural formulae can be written as:



and



The  $R^{2+}/R^{3+}$  ratios of octahedral layer are 1.4 for gray palygorskite and 3.8 for pink one. The  $\text{Fe}^{2+}$ ,  $\text{Ti}^{4+}$  and  $\text{Mn}^{2+}$  are omitted in the formulae due to their very low contents.

The mineral particles less than 2 microns in size were separated from the attapulgite clay by sedimentation and centrifuging in distilled water. No quartz diffractions were found in the XRD patterns of the mineral particles (Fig. 1), and no montmorillonites in the form of floccule or flake were found by means of TEM.

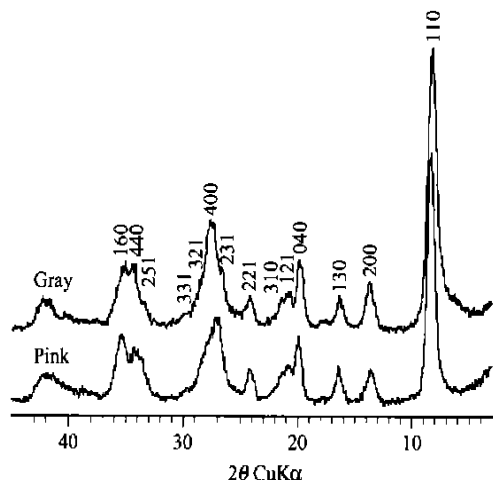


Fig. 1. Powder XRD patterns of two purified palygorskites.

The infrared absorption spectra of the purified samples were recorded on a Nexus 870 Fourier Transform Infrared Spectrometer (FTIR) in Modern Analysis Center of Nanjing University. The KBr pressed-disc was used to prepare FTIR samples. As can be seen in Fig. 2, the absorption bands for these two palygorskites are at  $3615\text{ cm}^{-1}$  ( $\nu\text{Al}_2\text{OH}$ ),  $3580\text{ cm}^{-1}$  ( $\nu(\text{Al, Fe})_2\text{OH}$ ),  $3417\text{ cm}^{-1}$  ( $\nu\text{Si-O-Si}$ ),  $3285\text{ cm}^{-1}$  ( $\nu\text{Si-O-Al}$ ). The latter two bands shift because of  $\nu\text{OH}$  vibrations of the hygroscopic

water. By comparison two vibrations of  $3686$  and  $3560\text{ cm}^{-1}$  appear in the spectrum of the pink one. These two vibrations were assigned to  $\nu\text{Mg}_3\text{OH}$  [10, 11], and  $\nu(\text{Fe}^{3+}, \text{Mg})\text{OH}$ , respectively. As mentioned above there are about 68% tri-octahedral component in gray palygorskite and 82% component in the pink one. That is, the  $\nu\text{Mg}_3\text{OH}$  and  $\nu(\text{Fe}^{3+}, \text{Mg})\text{OH}$  vibrations appear in the FTIR spectrum of the pink one, probably resulting from the higher trioctahedral components.

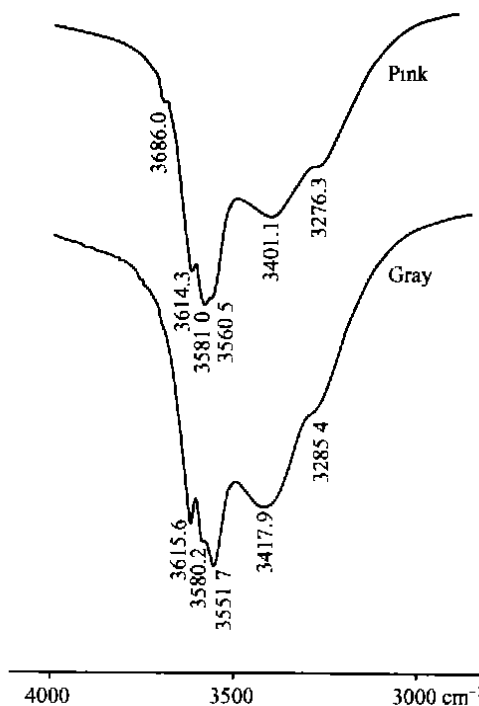


Fig. 2. FTIR spectra of two purified palygorskites.

## 2 Leaching experiments and results

The two palygorskites mentioned above were leached in HCl solution in batch reactors at room temperature. The solutions of 1, 3, and 5 mol/L HCl were employed to leach two palygorskites and the solid/liquid ratio was 3 g/300 mL for each experiment. The leaching time was controlled at 0.25, 0.5, 1, 1.5, 2, 3, 4, 5, 6, and 7 h, respectively. The equal amounts of suspension were extracted from the batch reactors at predetermined time and then centrifuged in a high speed centrifuge. The liquid was analyzed by means of ICP-AES. The ICP-AES testing was carried out by Modern Analysis Center in Nanjing University. Fig. 3 is plotted based on the analysis results. In the figure, the leachates were denoted by "g" or "p" followed by a number, where "g" and "p" represent gray palygorskite and pink

one, respectively. The following number is the concentration of the HCl solution, for example, "1"

means 1 mol/L HCl solution, etc.

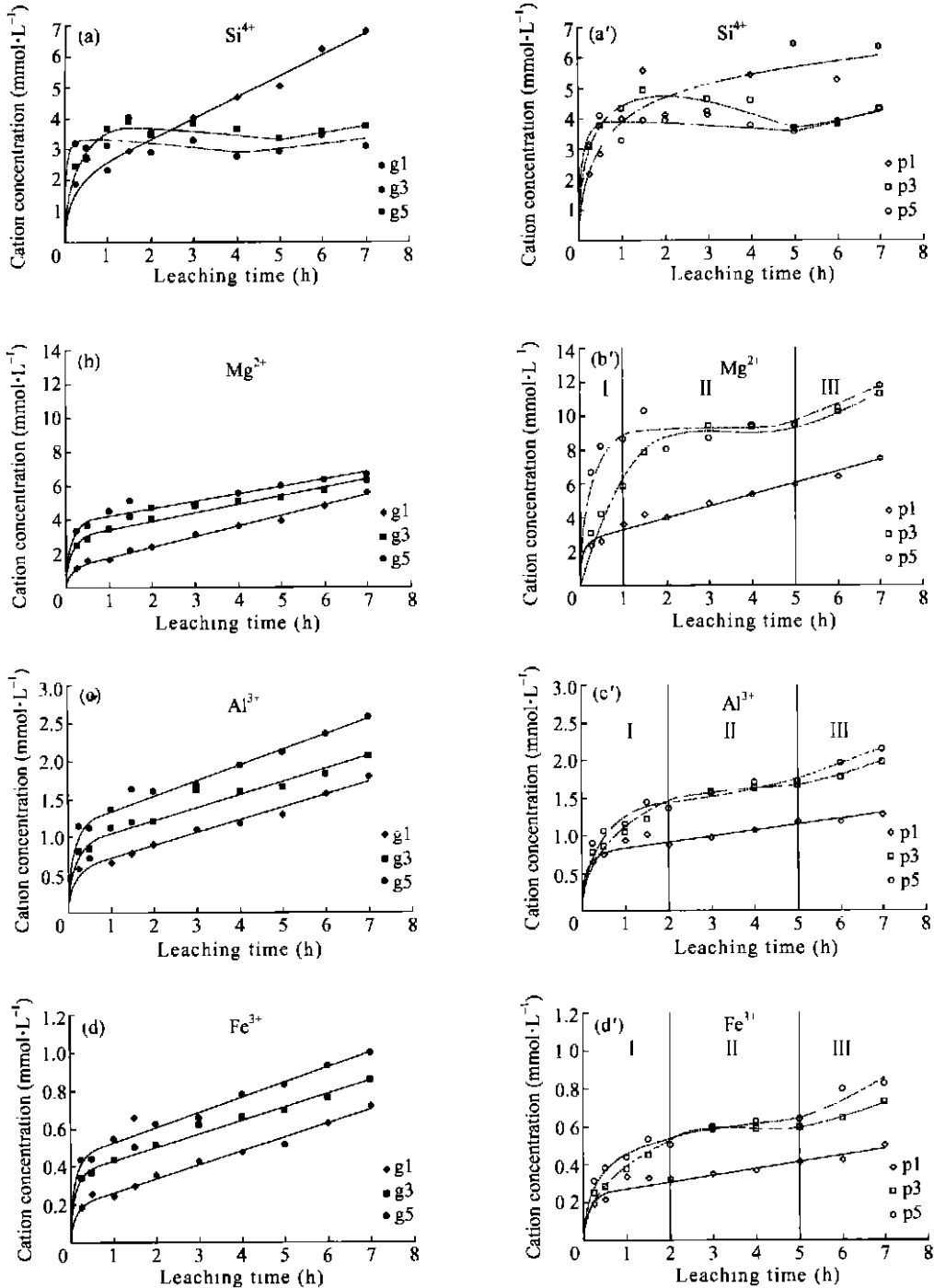


Fig. 3. Plots of cation concentrations in leachate versus leaching time for two palygorskites dissolved by 1, 3, and 5 mol/L HCl. (a), (b), (c), and (d): gray palygorskite (a'), (b'), (c'), and (d'): pink palygorskite.

As shown in Fig. 3, a and a' give the trends of  $Si^{4+}$  concentration in leachate versus leaching time in different concentrations of HCl solution of two palygorskites, respectively. As 1 mol/L HCl solution was used, the  $Si^{4+}$  concentration increased gradually. However at 3 and 5 mol/L HCl, at the beginning of

the leaching, namely within 0.5 h, the  $Si^{4+}$  concentration increased along with increasing of the acid concentration, and from 0.5 to 5 h, the concentration of  $Si^{4+}$  decreased and it was less than that in 1 mol/L at the same dissolution time. After 5 h, the  $Si^{4+}$  concentration is crescent. The concentration of  $Si^{4+}$  in

3 mol/L HCl is higher than 5 mol/L. In a word, the trends of  $\text{Si}^{4+}$  concentration in leachate versus leaching time could be divided into 3 steps. The  $\text{Si}^{4+}$  concentration versus time increases sharply at the beginning. The  $\text{Si}^{4+}$  concentration slightly decreases in the second step, and the decreasing slope much bigger in 5 mol/L than in 3 mol/L. The pink palygorskite in 1 mol/L also presents this step in which the curve is going up mildly. The third step is a gradually increasing step. The slope is much smaller than the first step.

Fig. 3(b), (c), (d), (b'), (c'), and (d') give the extracted trends of octahedral cation  $\text{Mg}^{2+}$ ,  $\text{Al}^{3+}$ ,  $\text{Fe}^{3+}$  in different concentrations of HCl solution of two palygorskites, respectively. As can be seen in the figures, the dissolution curves are different for two palygorskites. For gray palygorskite, the concentrations of octahedral cations are increasing with the increase of leaching time and the concentration of HCl solution. However, the same leaching trend was only seen in 1 mol/L HCl solutions for pink palygorskite. It is obvious that three steps can be considered for the pink one. The first step extends to 2 h. If the same concentration HCl solution is used, the cation concentration is increasing along with the elapsing of dissolution time, and the concentration of leached cations is much higher than in gray palygorskite at the same dissolution time. If the dissolution time is fixed and the higher HCl solution is used, the more octahedral cations can be extracted. The concentrations of leached cations were almost kept unchanged with the increase of HCl solution and elapsing of dissolution time for the second step. Like the extraction of  $\text{Si}^{4+}$ , the extraction octahedral cations are gently increasing with the time elapsing for the third step, and this step starts after 5 h.

### 3 Discussions

#### 3.1 Dissolution of $\text{Mg}^{2+}$ , $\text{Al}^{3+}$ , $\text{Fe}^{3+}$

It can be seen from Fig. 4 that the  $\text{Mg}^{2+}/(\text{Al}^{3+} + \text{Fe}^{3+})$  ratio increases gradually along with time elapsing at the beginning, and is steady at a constant value. The ratio value is 2 for gray palygorskite and  $>4$  for pink palygorskite. They are bigger than the  $\text{Mg}^{2+}/(\text{Al}^{3+} + \text{Fe}^{3+})$  ratio 1.4 for gray palygorskite and 3.8 for pink palygorskite of their unit formulae. Many researchers<sup>[2-5,7,8]</sup> concluded that the  $\text{Mg}^{2+}$  is more easily leached because it is at the edge of the octahedral ribbons. However, Heller-Kallai et al.<sup>[12]</sup>

and Augsburg et al.<sup>[13]</sup> proved that the  $\text{Fe}^{3+}$  is also at the edge of the octahedral ribbons by the Mössbauer spectra. Thus, it seems to us that it is difficult to explain why much more  $\text{Mg}^{2+}$  cations were leached from the crystal than  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$ . Corma et al.<sup>[2]</sup> considered that the  $\text{Mg}^{2+}$  is easier for extracting than  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$ . He et al.<sup>[14]</sup> researched the acid activating of montmorillonite, and found that  $\text{Mg}^{2+}$  was preferentially leached. That is, the  $\text{Mg}^{2+}/(\text{Al}^{3+} + \text{Fe}^{3+})$  ratio values in leachate for two palygorskites are higher than those in unit formulae, proving that  $\text{Mg}^{2+}$  is preferentially leached.

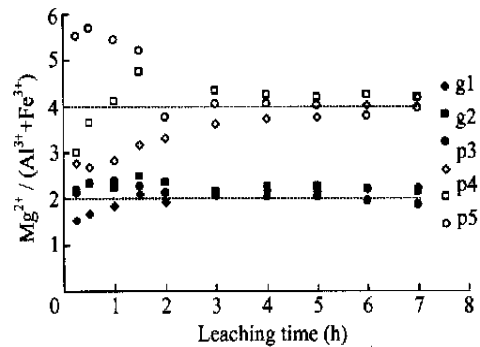


Fig. 4. Plot of  $\text{Mg}^{2+}/(\text{Al}^{3+} + \text{Fe}^{3+})$  versus leaching time for two palygorskites in HCl solution.

That the  $\text{Mg}^{2+}/(\text{Al}^{3+} + \text{Fe}^{3+})$  values in the leachates of 3 and 5 mol/L HCl solutions are bigger than 2 and 4 for two palygorskites respectively shows that  $\text{Mg}^{2+}$  was preferentially leached. According to the theory of ionic polarization and bond-strengths<sup>[15]</sup>,  $\text{Mg}^{2+}$  could be easily extracted into acid solution from the crystal. As the three cations composed octahedral coordination with oxygen, the strength of the ionic linkage is influenced by the ability of ionic polarization. The radius of  $\text{Al}^{3+}$ ,  $\text{Fe}^{3+}$  and  $\text{Mg}^{2+}$  is 0.0535, 0.055, 0.072 nm, respectively, so the order of the ability of ionic polarization is  $\text{Al}^{3+} > \text{Fe}^{3+} > \text{Mg}^{2+}$ , and the strength of the ionic linkage is  $\text{Al-O} > \text{Fe-O} > \text{Mg-O}$ . In addition, according to the theory of electrostatic bond<sup>[15]</sup>  $S = Z/n$  ( $S$ , strength of electrostatic bond;  $Z$ , charge numbers;  $n$ , coordinate numbers), the  $S$  of  $\text{Al}^{3+}$ ,  $\text{Fe}^{3+}$  and  $\text{Mg}^{2+}$  is 0.5, 0.5, and 0.33. According to the capability of ionic polarization and strength of electrostatic bond for these three cations, the  $\text{Mg-O}$  bond is most easily broken by  $\text{H}^+$ , then  $\text{Fe-O}$  bond, and at last the  $\text{Al-O}$  bond. Corma et al.<sup>[8]</sup> calculated the activation energies of these three cations of Spanish palygorskites, and concluded that the activation energy of  $\text{Al}^{3+}$  is greater than that of  $\text{Fe}^{3+}$ , and that of  $\text{Fe}^{3+}$  is greater than  $\text{Mg}^{2+}$ . It was in agreement with the above-

mentioned results. In other words, in these cations the  $Mg^{2+}$  was most easily extracted into acid solution. Myriam et al.<sup>[17]</sup> found that sepiolite is more easily collapsed by acid attack than palygorskite and attributed it to the higher content of  $Mg^{2+}$  in sepiolite. The leaching result of two palygorskites with different amounts of  $Mg^{2+}$  shows that the higher content of  $Mg^{2+}$  is much easier subjected to erosion by HCl solution at the same concentration.

### 3.2 Dissolution of $Si^{4+}$

It is well known that the  $H_4SiO_4$  is the first product during the dissolution of silicates in acid solution<sup>[16~19]</sup>. The experimental results explained that the  $Si^{4+}$  concentration increased gradually with time elapsing, and the leached cation concentration in lower concentrations of acid can exceed the higher concentration. It seemed that the size of the  $H_4SiO_4$  colloid is varying, and the colloids suspend when the dissolution is in the low state, namely the low concentration of acid or shorter leaching time. It can be tested by ICP-AES. Schott et al.<sup>[20]</sup> detected the amorphous silica by SEM at the surface of chain silicates which had been dissolved in acid. He et al.<sup>[14]</sup> also tested that there was amorphous silica by MAS NMR in acid activation experiment of montmorillonite. Hence, the slowly elevating step of  $Mg^{2+}$  and  $Si^{4+}$  may show that the amorphous silica is adsorbed onto the surface of the palygorskite, and the extraction of the cations is temporarily obstructed. As a consequence, the leaching process of the minerals is hindered. If the dissolution develops to a high level (high concentration of HCl solution and much longer leaching time), along with the size increasing of the silica particulates, or increasing of the acid concentration, the silica particulates flocculate, and precipitate. Thus the  $Si^{4+}$  concentration decreases in the leachate.

### 3.3 Conditionality of leached $Si^{4+}$ and $Mg^{2+}$

Fig. 3 (b) and (b') reveal that the leached  $Mg^{2+}$  concentration of pink palygorskite at 0.5 h leaching is much higher than the concentration of gray palygorskite at 7 h in 5 mol/L HCl solution. Fig. 3(a) and (a') show that the leached  $Si^{4+}$  concentration of pink palygorskite is higher than that of gray palygorskite in the same concentration of HCl solution. Consequently, the leaching rate of pink palygorskite is much faster than that of gray palygorskite. In other words, higher content of  $Mg^{2+}$  in pink palygorskite results in a higher dissolution rate

when it is attacked by the HCl solution. Due to its fast dissolution rate, the collapse of octahedral layer accelerates the extraction of  $Si^{4+}$ , and makes the shift point between the first step and the second step appear earlier than gray palygorskite (0.5 h for pink palygorskite, and 1 h for gray palygorskite). After this point, the  $Mg^{2+}$  concentration in leachate goes up more slowly. After 5 h, the  $Mg^{2+}$  and  $Si^{4+}$  concentration increase gradually with the time elapsing according to Fig. 3. It resulted from the fact that after the silica was flocculated and precipitated, the structural channels of the palygorskite were reopened, so that  $Mg^{2+}$  was re-extracted from the crystals.

The conditionality of  $Mg^{2+}$  and  $Si^{4+}$  gives the three steps to dissolution curves as the palygorskite is leached by the HCl solution, but the model is not obvious in gray palygorskite. It could be suggested that pink palygorskite has a very high  $Mg^{2+}$  content, and it has a sharp slope in the much earlier dissolution process, so the point between two steps can be clearly shown when their extraction to HCl solution slows down.

### 3.4 Leaching mechanism of $Mg^{2+}$ , $Al^{3+}$ , $Fe^{3+}$

As can be seen in Fig. 4, the  $Mg^{2+}/(Al^{3+} + Fe^{3+})$  ratio increases steadily with leaching time and then reaches a constant value in leached solution of 1 mol/L HCl. However as it leached by 3 and 5 mol/L HCl, the  $Mg^{2+}/(Al^{3+} + Fe^{3+})$  ratio becomes a bigger value, and then decreases to a constant value of 2 for gray palygorskite, and  $> 4$  for pink palygorskite. The different dissolution among different concentration of HCl solution indicates that the concentration has influenced the extraction rate of  $Mg^{2+}$ . Based upon this fact, it is believed that at the earlier stage of dissolution by 1 mol/L HCl, the extraction of the cations is controlled by diffusion mechanism, i. e. the cations diffuse from the crystal surface to the solution, and the  $H^+$  from solution to the surface. Initially, not only the octahedral cations, but also the tetrahedral cations with  $Al^{3+}$  in tetrahedron site are exposed on the surface of the crystal. Therefore, the  $Mg^{2+}/(Al^{3+} + Fe^{3+})$  ratio is lower. The chemical reaction gradually becomes a leading factor along with the developing of the dissolution. The preferential leaching of  $Mg^{2+}$  results in the gradual increase of  $Mg^{2+}$  concentration. The penetration of the  $H^+$  from solution to the inner structural channels of the crystal makes the leaching throughout the channels, and the  $Mg^{2+}/(Al^{3+} + Fe^{3+})$  ratio reaches a constant value.

The leaching behavior in higher concentration of 3 and 5 mol/L HCl shows that the chemical reaction appears easier. Because of the diffusion superposed on the chemical reaction, much more  $Mg^{2+}$  is leached, especially for pink palygorskite. The  $Mg^{2+}/(Al^{3+} + Fe^{3+})$  value does not keep steady until the  $H^+$  diffuses into all structural channels.

## 4 Conclusions

(1) The structural formulae of two Guanshan palygorskites from Anhui Province showed that their crystal structures had different contents of trioctahedral occupation. The contents of trioctahedral occupation are 82% for pink palygorskite and 68% for gray palygorskite. Thus the former had the absorption band at  $3686\text{ cm}^{-1}$  for its FTIR spectrum. The  $S_{BET}$  of these two palygorskites are  $214\text{ m}^2\cdot\text{g}^{-1}$  for the pink one and  $182\text{ m}^2\cdot\text{g}^{-1}$  for the gray one, respectively. They have the same dissolution behavior in 1 mol/L HCl solution. The concentration of  $Mg^{2+}$  increased gradually along with the dissolution time. Nevertheless, three steps had to be considered for the leaching of  $Mg^{2+}$ ,  $Al^{3+}$ , and  $Fe^{3+}$  in overall reaction in 3 and 5 mol/L HCl leachates, i.e., fast extracting step, extracting step, and reextracting step.

(2) That the leached concentrations of cation for pink palygorskite versus leaching time are obviously divided into three steps can be attributed to the higher  $Mg^{2+}$  content. The preferential selectivity of  $Mg^{2+}$  and the lowest activation energy in HCl solution lead to the faster erosion of pink palygorskite. After a sharply leaching of cations, amorphous silica hindered the diffusion of  $H^+$  from solution to channels of crystal structure, and the dissolution curve is turned to a gentle slope. Due to the flocculation of the amorphous silica, the micro-channels in the crystal structure are reopened, and the dissolution is promoted.

(3) As two palygorskites are dissolved by the HCl solution, the  $Mg^{2+}/(Al^{3+} + Fe^{3+})$  ratio may reach a constant value. The values are related to the original chemical composition of palygorskite, and reach the value from a lower value to 2 for gray palygorskite and 4 for pink palygorskite in lower acid concentration, for example, 1 mol/L. It is believed that the  $H^+$  has been penetrated throughout the structural channels of the crystal, reacted with crystal, and reached a chemical equilibrium. The higher the concentration of acid is employed, the shorter time it takes to reach a constant value.

**Acknowledgement** The authors would like to thank Prof. Fang Jinman for his kind help in field work. The authors would also thank Dai Lemei and Chen Yijun for their careful ICP-AES testing.

## References

- Jones B. F. et al. Sepiolite and palygorskite. In: Bailey, S. W. ed. *Hydrous Phyllosilicates (Exclusive of micas)*. Washington, D. C.: Mineralogical Society of America, 1988, 19: 632.
- Corma A. et al. Influence of the chemical composition and textural characteristics of palygorskite on the acid leaching of octahedral cations. *Clay Minerals*, 1987, 22(2): 225.
- Feng, Q.M. et al. The study on acid activation conditions and way of dolomitic palygorskite clay on Huangzhong County, Qinghai Province. *Non-Metallic Mines (in Chinese)*, 1999, 22(4): 11.
- Yi, F. C. et al. The activation of palygorskite clay. *Multipurpose Utilization of Mineral Resources (in Chinese)*, 1996, (6): 19.
- Yi, F. C. et al. The acid activation and absorption capability study of palygorskite. *Multipurpose Utilization of Mineral Resources (in Chinese)*, 1995, (6): 41.
- Gonzalez F. et al. Mechanism of acid activation of magnesian palygorskite. *Clays and Clay Minerals*, 1989, 37(3): 258.
- Myriam, M. et al. Structure and textural modifications of palygorskite and sepiolite under acid treatment. *Clays and Clay Minerals*, 1998, 46(3): 225.
- Corma A. et al. Kinetics of the acid leaching of palygorskite: Influence of the octahedral sheet composition. *Clay Minerals*, 1990, 25(2): 197.
- Cai Y. F. et al. Compositions and infrared spectra of two kinds of Guanshan palygorskite clay. *ACTA Mineralogica Sinica (in Chinese)*, 2001, 21(3): 323.
- Ahrlrichs, J. L. et al. Structure hydroxyls in sepiolites. *Clays and Clay Minerals*, 1975, 23(1): 119.
- Chahi A. et al. Infrared evidence of dioctahedral-trioctahedral site occupancy in palygorskite. *Clays and Clay Minerals*, 2002, 50(3): 306.
- Heller-Kalhai L. et al. Mössbauer studies of palygorskite and some aspects of palygorskite mineralogy. *Clays and Clay Minerals*, 1981, 29(3): 226.
- Augsburger M. S. et al. FTIR and Mössbauer investigation of a substituted palygorskite: Silicate with a channel structure. *Journal of Physics and Chemistry of Solids*, 1998, 59(2): 175.
- He, H. P. et al. A microstructural study of acid-activated montmorillonite from Choushan, China. *Clay Minerals*, 2002, 37(2): 337.
- Deng, J. F. et al. *Physical Chemistry*, 1st edition (in Chinese). Beijing: Advanced Educational Press, 1993, 465~467.
- Dove P. M. The dissolution kinetics of quartz in aqueous mixed cation solutions. *Geochimica et Cosmochimica Acta*, 1999, 63(22): 3715.
- Dove, P. M. et al. Kinetics of quartz dissolution in electrolyte solutions using a hydrothermal mixed flow reactor. *Geochimica et Cosmochimica Acta*, 1990, 54(4): 955.
- Dove, P. M. et al. Silica-water interactions. In: Heaney, P. J. et al. eds. *Silica: Physical Behavior, Geochemistry, and Materials Applications*. Washington, D. C.: Mineralogical Society of America, 1994.
- Lasaga A. C. Atomic treatment of mineral-water surface reactions. In: Hochella Jr. M. F. et al. (eds) *Mineral-Water Interface Geochemistry*. Washington D. C.: Mineralogical Society of America, 1990.
- Schott, J. et al. Mechanism of pyroxene and amphibole weathering—I. Experimental studies of iron-free minerals. *Geochimica et Cosmochimica Acta*, 1981, 45(11): 2123.