

Cation Exchange Capacities, Swelling, and Solubility of Clay Minerals in Acidic Solutions : A Literature Review

Won Choon Park

Abstract: A literature review is made on the physical and chemical characteristics of clay minerals in acidic solutions from the mineralogical and hydrometallurgical viewpoints. Some of the important characteristics of clays are their ability to cation exchange, swelling, and incongruent dissolution in acidic solutions. Various clay minerals can take up metallic ions from solution via cation exchange mechanism. Generally, cation exchange capacity increases in the following order : kaolinite, halloysite, illite, vermiculite, and montmorillonite. In acidic solutions, the cation uptake such as copper by clay minerals is strongly inhibited by hydrogen and aluminum ions and thus is not economically significant factor for recovery of metals such as uranium and copper. In basic solutions, cation uptake is substantial.

Swelling is minimal at lower pH, possibly due to lattice collapse. Swelling may be controllable with montmorillonite type clays by exchanging interlayer sodium with lithium and/or hydroxylated aluminum species.

The effect of acid on clay minerals are :

1. Division of aggregates into smaller plates with increase in surface area and porosity.
2. Clay-acid reactions occur in the following order : (i) H^+ replacement of interlayer cations, (ii) removal of octahedral cations, such as Al, Fe, and Mg, and (iii) removal of tetrahedral Al ions. Acid attack initiates around the edges of the clay particles and continued inward, leaving hydrated silica gel residue around the edges.
3. Reaction rates of (ii) and (iii) are pseudo-1st order and proportional to acid concentration. Rate doubles for every temperature increment of $10^\circ C$.

Implications in in-situ leaching of copper or uranium with acid are :

1. Over the life span of the operation for a year or more, clays attacked by acid will leave silica gel. If such gel covers the surface of valuable mineral surfaces being leached, recovery could be substantially delayed.
2. For a copper deposit containing 0.5% each of clay minerals and recoverable copper, the added cost due to clay-acid reaction is about 1.5c/lb of copper (or 0.93 lbs of H_2SO_4 /lb of copper). This acid consumption by clay may be a factor for economic evaluation of in-situ leaching of an oxide copper deposit.

Introduction

Clay minerals are widely distributed in soils and rocks. Most metallic and non-metallic ores contain variable amounts of clay minerals. These minerals affect physical and chemical process parameters such as grindability, flotation response, fluid flow in rocks, and reactivity between ore minerals and lixiviant. In view of these, a brief literature review was made. This review is concerned with the characteristics of clays in regard to their cation exchange capacities,

swelling, and chemical reactions in acidic solutions.

Information presented in this review is applicable to hydrometallurgical treatment of ores, such as in-situ leaching of copper and uranium deposits, recovery of Al_2O_3 and MgO from the spent shale, and acidulation treatment of sedimentary phosphate of ores.

Cation exchange capacities

Introduction : Clay minerals are capable of acting as ion-exchange material in hydrometal-

lurgical treatments. This exchange capability varies depending on the type of clay minerals (see Appendix) under a given physico-chemical condition. For example, kaolinite has a low ion-exchange capacity, about 3~15 milli-equivalent/100g (0.2~0.5wt% Cu), because exchange is limited to broken bonds and hydroxyl group at the edges or corners of the layers. On the other hand, montmorillonite exhibits a higher exchange capacity, about 20~150 milli-equivalent/100g (0.7~4.8wt%), because inter-layer bonding is weak.

At a given temperature and solution chemistry, cation exchange capacities of clay minerals increase in the following order (Grim, 1968): kaolinite, halloysite, illite, vermiculite, and montmorillonite.

Figure 1 (various sources) shows copper uptake of these clay minerals vs pH.

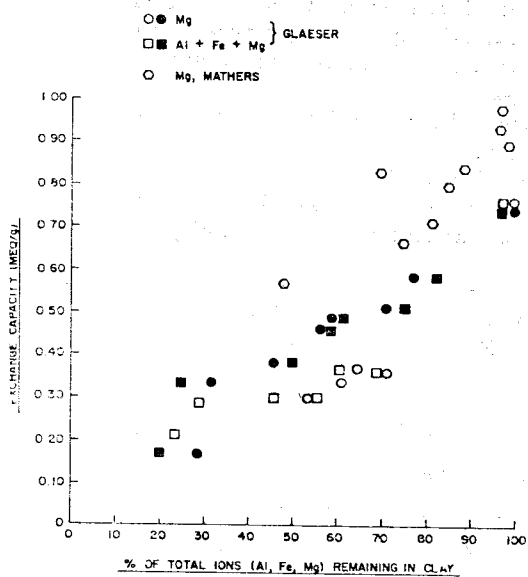


Fig. 1 Copper uptake vs pH of various clay minerals from CuSO_4 solution (0.63% Cu/1 except montmorillonite-containing solution at 0.98g Cu/1)

Copper uptake decreases as pH of the solution decreases (Block and Charbonnelle, 1958). Uptake values from approximately 1g Cu/1 solution are:

	wt% Cu exchanged	
	pH=2	pH=4
Kaolinite	0.03	0.08
Halloysite	0.04	0.16
Illite	0.09	0.22
Montmorillonite	0.82	1.56

Thus, lowering of pH of the solution during leaching of the oxide ores is advantageous, in addition to a higher copper loading at lower pH.

Above data show that 0.5% montmorillonite in a 0.5% Cu deposit can take up maximum 0.8% of the total copper at pH=2 and 1.6% of the total copper at pH=4.

Copper uptake (exchange capacity): Cation selectivity on exchangeable clay minerals is influenced by solution concentration, ionic size and valence, ion hydration, and by structural and charge properties of specific clay minerals. In general, the exchangeability increases (a) with decreasing hydrated radius and increasing polarity, (b) with increasing cation charge, and (c) with decreasing ease of cation hydration.

Relative affinities of metal ions for montmorillonite are $\text{Cs} > \text{Rb} > \text{K} > \text{H} > \text{Na} > \text{Li}$.

Heydemann (1959) showed that copper can be incorporated into clay minerals by an ion-exchange mechanism. Weiss and Amstutz (1966), working with zeolites, found that copper is more strongly held than other transition metals; $\text{Cu} > \text{Pb} > \text{Ni} > \text{Ag} > \text{Zn} > \text{Hg} > \text{Cd}$. Generally for clay minerals, the affinity of various metals, as measured by Ovcharenko (1969) is $\text{Cu} > \text{Co} > \text{Mn} > \text{Ca} > \text{NH}_4 > \text{Na}$.

Trask (1968) observed that above pH 2.1, altered volcanic rocks from a montmorillonite zone could take up to 0.3wt% Cu.

Ion-exchange reactions on clay minerals are generally reversible. There are, however, exceptions as, e. g., in cation fixation when a fraction of the exchange is irreversible; Hower (1955), for example, could not exchange a sub-

stantial amount of copper in montmorillonite with CsCl solution. Also, copper could not be replaced by exchange in synthetic copper vermiculites (Bassett, 1958). Such irreversibility indicates that copper ions are trapped between unit layers that have collapsed together (lattice collapse).

Effect of aluminum in CEC : Below neutral pH, the dissolved aluminum species consist of three forms, (1) the monomeric octahedral Al $(\text{H}_2\text{O})_6^{+3}$, $\text{AlOH}(\text{H}_2\text{O})_5^{+2}$, $\text{Al}(\text{OH})_2(\text{H}_2\text{O})_4^+$, and $\text{Al}(\text{HO})_4(\text{H}_2\text{O})_2^-$ ions, (2) a positively charged polymeric species held together by double hydroxide bridges, and (3) hexagonal microcrystalline gibbsite $\text{Al}(\text{OH})_3$ particles (Brown and Hem, 1975). It is known that concentrations of $7\sim 7\text{g/l}$ Al^{3+} in an acidic solution, such as found in dump leach operations, are sufficient to depress the copper uptake by clays. In the absence of aluminum in the solution, the cation exchange positions would be occupied by H^+ and cations such as Na^+ , Cu^+ etc, in proportion dictated by pH.

Swelling

Adsorption of water by clays results in expansion or swelling. Water molecules are adsorbed either externally onto or internally between clay unit layers. Swelling of expanding clays is believed to occur as follows (Swartzen-Allen and Matijevic, 1974). The initial hydration of the internal surfaces and of the interlayer cations takes place stepwise. When several layers of water have been adsorbed between the unit layers, osmotic forces caused by the relatively high ionic concentrations between the layers lead to a continuous swelling. Degree of swelling depends on the clay mineralogy, exchangeable ions, electrolyte content of the aqueous phase, particle size, pressure etc. The following tabulation shows the amount of free swelling by various clay minerals (Mielenz and King, 1955).

	<u>Free-swelling (% increase)</u>
Ca-montmorillonite	50~150
Na-montmorillonite	1400~2000
Illite	15~120
Halloysite	70
Kaolinite	5~60

With montmorillonite type clays, swelling decreases greatly when sodium is replaced by other cations such as lithium and hydroxylated aluminum species. This is possibly due to cation fixation and lattice collapse, rendering the interlayer region relatively inaccessible with respect to water penetration. The sequence of decreased swelling in general is : Na, Li, K, Rb, NH_4 , Cs, Mg, Ca, and Ba. Some clay swelling is expected during acidic in-situ mining operation, but not at a level of pure water system. Since H^+ will replace interlayer cations of clays or dissolve Al and Mg from the structure in acid leaching, deleterious effect due to swelling would be minimal.

Effects of acids on clay minerals

Introduction : The solubility of clay minerals in acids was summarized in Grim's textbook (1968). Published results have applications in the areas of soil science, bonding of refractories by acid media, decolorizing oils, and of catalysts for petroleum refinery. None of the available data provide the total information such as the relationship of acid consumption to the degree of alteration. Usually in a given set of experiments only one functional dependence was ascertained. For example, aluminum extraction was measured as a function of time or acid strength in one instance and in another set of data aluminum extraction was measured as a function of time or acid strength in one instance and in another set of data aluminum extraction was measured as a function of temperature for a fixed period on different clay minerals. Therefore, it is difficult to combine all the published

data for a quantitative analysis and assessment of the clay-acid reaction.

Clay-acid reactions : Clays of the montmorillonite-beidellite group are more easily attacked by dilute acids than silicates of the kaolinite, mica, talc, or pyrophyllite groups. In pure water, montmorillonite dissolves to the extent of at least 36 ppm. The proportion in solution was found to be richer in silica than the original clay (Nutting, 1932 and 1943). In dilute acids (0.1~0.4%), bases and silica dissolve in the same proportion as in the original clay.

Solubility of silica decreases with increasing acid concentration and reaches zero solubility for 24% HCl at 90°C. Ions in the exchangeable position are readily removed by 0.1% HCl at 90°C within 48 hrs. or 10% HCl at room temperature within 6 hrs. With more concentrated acids (10~30%) and higher temperature (50 to 100°C) the base ions in octahedral positions can be completely removed in several days. The residue is composed of Si-O tetrahedral networks which become amorphous to X-rays. This result was reported by Brindley and Youell (1951) for a magnesian chlorite (penninite) and by Mering (1949) in his studies of acid activation of montmorillonite. They also found that by treating the residue with a solution containing the appropriate ions it is possible to reconstitute a mica-like ($C=10\text{\AA}$) and, in the case of clay, a montmorillonite-like product. Hence the acid-clay reaction appears to be a reversible one. The silica residue can be dissolved with alkaline solution (5% Na_2CO_3 for 1 hour at 80°C). Results on alternate treatments with HCl and NaOH was also reported by Otsubo (1953).

Specific surface area of clays treated with acid was studied by Longuet-Escard et al (1950), and by Alvarez (1969). The specific surface, as measured by gas adsorption, initially in-

creases to a maximum and then decreases as increasing amount of Al, Fe, and Mg oxides were removed. This behavior can be explained in terms of an initial division of the aggregate clay particles into smaller particles, the distortion of crystal lattice, and the subsequent conversion of the clays to amorphous silica. Gas adsorption on acid treated silicates was also made by Kato et al (1966), using CH_4 , C_3H_8 and CO_2 with H_2 as a carrier. Increase of surface area and porosity of montmorillonite treated with H_2SO_4 (96°C for 6 hrs) was reported by Belik (1973).

Reaction kinetics : Decomposition of montmorillonite by HCl was studied by Gregor et al (1966). The reaction kinetics for the extraction of Fe and Al was found to be pseudo-1st order, with an activation energy of 21 kcal/mole. Al release from kaolinite and montmorillonite of different size fractions by 3.6N HCl dissolution was studied by Miller (1965). The decrease of kaolinite lattice Al concentration was linear with time, satisfying the condition for a pseudo-zero order reaction. For montmorillonite, the log (lattice Al) decreased linearly with time to fit a pseudo-1st order reaction. A diffusion controlled edge attack was proposed for kaolinite (similar to the behavior of biotite as reported by Gastuche (1963), and an all surface attack for montmorillonite. For kaolinite the reaction kinetics depend on particle size, but the rate of Al release in montmorillonite is independent of particle size. Dissolution of nontronite and montmorillonites was studied by Osthaus (1953 and 1956) using 10~30% HCl and a temperature range of 70~100°C. The rate of dissolution of octahedral Al, Mg and Fe are identical for each clay. The observation, that Al, Fe and Mg in the smectites were removed in the same proportions as they occurred in the clay, was also reported by Mathers et al. (1956). The same conclusion can be drawn from the data of Gla-

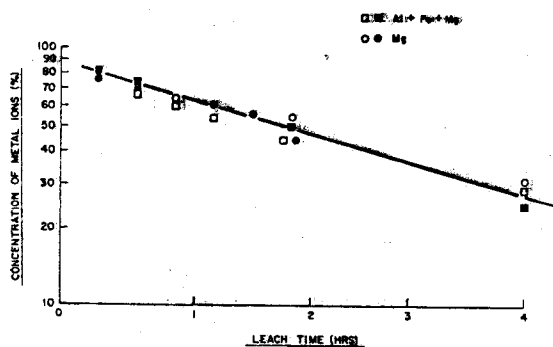
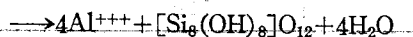


Fig. 2. Dissolution of 2 montmorillonite in boiling 30% H₂SO₄ (Gieseler (1946) as shown in figure 2. This conclusion is in contrast to the earlier results as quoted by Grim. Osthaus found that the measured rate constant is directly proportional to the acid concentration (for a range of 10~30% HCl). In addition, he also found that the rate doubles for each temperature increment of 10° C. For example, the rate for the extraction of octahedral Al from montmorillonite was found to be 0.005/hr at 53.8°C and 0.022/hr at 72.3°C (10% of HCl). The tetrahedral Al extraction rate is lower than the octahedral rate possibly due to higher bonding strength. The activation energy was found to be 17~18kcal/mole for both tetrahedral and octahedral ions. A higher value of 21 kcal/mole was obtained by Gregor. In general, Osthaus found that the rate constant varies, depending on the source of clay but the temperature and acid concentration dependence is not a function of clay origin.

A model of acid activation of clay was developed by Thomas et al (1950) where he discussed the structural formula of clay with increasing acid attack resulting in a final silica residue of [Si₈(OH)₈]O₁₂. One can estimate the acid consumption for the total destruction of clay by using an idealized initial clay formula of [Al₄][Si₈](OH₄)O₂₀. The following reaction can be used: [Al₄][Si₈](OH₄)O₂₀ + 12H⁺



This reaction should consume 1.17g H₂SO₄/g clay.

The actual redistribution of charges, due to the substitution of Mg and Fe for Al in the octahedral layer and the existence of exchangeable alkaline cation layers, should not alter this value as long as the initial clay has zero charge. A significant amount of Al substitution in the silica tetrahedral layer could affect this estimate.

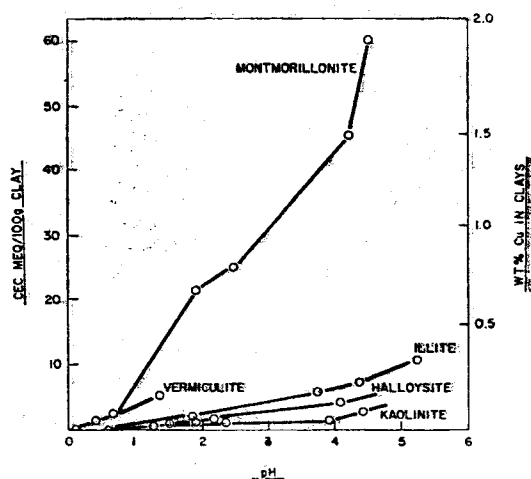


Fig. 3. Dependence of CEC on the octahedral cation concentration in montmorillonites.

Effects of acid on the cation exchange capacity (CEC): A decrease of CEC of clays due to acid treatment was found by Kato (boiling 5~30% H₂SO₄) and by Komarov et al on calcined clays treated with HCl, H₂SO₄, and HNO₃. A linear decrease of CEC with increasing dissolution of octahedral cations is evident from the data of Mathers, Glaser and Nikolaev et al. These results are shown in figure 3. This decrease in CEC is related to the destruction of clay by acid and implies that the silica residue does not appear to have any significant exchange capacity.

Implications in in-situ leaching of copper:

a. Kinetic Effects—From the data of Glaeser,

where 80% of the octahedral cations were dissolved in 5 hours in boiling 30% H_2SO_4 , one can estimate that an 80% dissolution can be achieved under an in-situ condition (10% H_2SO_4 at 30°C) in 60 days.

Using the data of Thomas (45% dissolution in 6.5 hours with boiling 10% HCl), 80% dissolution with 10% HCl at 30°C will require 10 days. The rate value of Osthaus, again for 80% dissolution with 10% HCl at 30°C, predicts a time scale of 8 days.

b. Acid consumption by clays—Assume :

- (1) for total dissolution of clays leaving silica residue, requires 1.17g H_2SO_4 /g clay.
- (2) 0.5% of accessible clays in a copper deposit.
- (3) grade : 0.5% of recoverable Cu.
- (4) acid price: \$30/ton.

Dissolution of 80% of clays in this deposit will require 9.36 lbs of H_2SO_4 /ton of rock, or 0.93 lbs of H_2SO_4 /lb of recoverable copper.

The added cost due to clay-acid reaction alone is 1.5¢/lb of copper, or 2.3% of the present copper price of 65¢/lb. For 100% destruction of clay, 11.7 lb H_2SO_4 /ton rock is required. This acid consumption by clay alone be a factor for economic evaluation of in-situ leaching of an oxide copper deposit.

Appendix

Classification of clay minerals

Clay minerals are composed of small plate-like particles ranging in diameter from a few hundredths of a micron to several microns. These plates are stacked like a deck of cards. The crystal structure of unit layers consist of sheets of tetrahedrally coordinated silica in combination with sheets of octahedral alumina or magnesia. In tables 1-4, the crystal-chemical classification of clay minerals is summarized. For details refer to Brown (1961), Jasmund (1955),

and Grim (1968).

The basic scheme of the clay classification is based on how oxygen-tetrahedral layers and

Tab. 1 Two-Layer Silicates (T : O-layer = 1 : 1 type)

	Non-Hydrated		Hydrated
O-sheet	Al	Mg	Al
T-sheet	dioctahedral	trioctahedral	diocahedral
Si	Kaolinite group $Al_4(OH)_8Si_4O_{10}$ 7A	Serpentine group $Mg_6(OH)_8Si_4O_{10}$ 7A	Halloysite group $Al_4(OH)_8Si_4O_{10} \cdot 4H_2O$ 10A

oxygen-hydroxy-octahedral layers are stacked on each other.

Tab. 2 Non-hydrated Three-layer Silicates (2 : 1 type)

	Predominantly Al diocahedral	Predominantly Mg, Fe^{3+} trioctahedral
O-sheet		
T-sheet		
Si $x=0$	Pyrophyllite $Al_2(OH)_2Si_4O_{10}$ 9.3A	Talc $Mg_3(OH)_2Si_4O_{10}$ 9.4A
SiAl $0 < x < 1$	deficient diocahedral mica dioc. illite, glauconite 10A	deficient trioctahedral mica trioct. illite 10A
Si ₃ Al $x=1$	diocahedral mica Muscovite $KAl_2(OH)_2Si_3AlO_{10}$ 10A	trioctahedral mica Biotite $KMg_3(OH)_2Si_3AlO_{10}$ 10A

x = layer charge, negative

Tab. 3 Hydrated Three-layer Silicates (2 : 1 type)

	Predominantly Al diocahedral	Predominantly Mg, Fe^{3+} trioctahedral
O-sheet		
T-sheet		
Si, Al $0 < x < 0.5$	Montmorillonite $(Al, Mg)_2(OH)_2(Si, Al)_4O_{10} (Ca, Na, \dots)_x \cdot mH_2O$	Saponite $(Mg, Fe^{2+}, Al)_3(OH)_2(Si, Al)_4O_{10} (Ca, Na, \dots)_x \cdot mH_2O$
Si, Al $0 < x < 1$	deficient diocahedral mica dioc. illite, glauconite dioc. vermiculite	deficient trioctahedral mica trioct. illite trioct. vermiculite
Si, Al $0.5 < x < 0.8$	$(Al, Mg)_2(OH)_2(Si, Al)_4O_{10} (Ca, Na, \dots)_x \cdot mH_2O$ 14A	$(Mg, Fe^{2+}, Al)_3(OH)_2(Si, Al)_4O_{10} (Mg, Ca, \dots)_x \cdot mH_2O$ 14.4A

The two-layer minerals consist of a single tetrahedral (T-sheet) and a single octahedral layer (O-sheet) (table 1). The three-layer minerals consist of a single O-sheet and two T-sheet layers (tables 2 and 3).

The four-layer minerals have an additional discrete octahedral layer between two three-layer pockets (table 4).

Tab. 4. Four-Layer Silicates (2:2 type)

O-sheet	Al dioctahedral	Predominantly Mg, Fe ²⁺ trioctahedral
	Sudoite Al ₂ (OH) ₂ Si ₄ O ₁₀ ·Al ₂ (OH) ₆ 14Å	Chlorite (Mg, Fe, Al) ₃ (OH) ₂ (Si, Al) ₄ O ₁₀ ·(Mg, Fe) ₃ (OH) ₆ 14Å

Dioctahedral minerals contain Al exclusively or predominantly in two-thirds of the available octahedral sites. Trioctahedral minerals have all of the available octahedral sites occupied completely or predominantly by Mg and Fe³⁺. A negative layer charge, x , can occur if Si in the tetrahedral coordination is replaced partially by Al. This negative charge is neutralized by interlayer positive charge. Hydrated layer silicate minerals contain interlayer water between the silicate pockets.

The kaolinite group consists of the three following polytypes:

- Kaolinite : 1T kaolinite
- Dickite : 2M kaolinite
- Nacrite : 4M kaolinite

Above kaolinite species are distinguished by the number of elementary layers per unit cell (1, 2, or 4) and the resulting symmetry (T for triclinic; M for monoclinic). 1T kaolinite, forming at low temperatures, is probably the most stable form.

The minerals of the serpentine group are antigorite (platy variety) and chrysotile (fibrous variety). Like the clay mineral halloysite, chrysotile fibers consist of individual hollow tubes.

Berthierite-cronstedite group minerals are not tabulated. These are trioctahedral minerals with a layer thickness of 7Å, which differ from serpentine by greater substitution of tetrahedral Si by Al and Fe³⁺. All trioctahedral two-layer minerals, because of chemical similarities to chlorite, are called collectively sepiochlorite.

Dioctahedral deficient mica differs from muscovite in that it contains less Al in tetrahedral and more Fe²⁺ and Mg substituting for octahedral Al. Its layer charge is less than that of muscovite, and accordingly it contains less K. Illite is a deficient mica, with reduced tetrahedral Al, predominantly Al in octahedral positions, and also reduced K-content. Glauconite is a deficient mica with lower tetrahedral Al-content, with much Fe³⁺ in addition to Fe²⁺, Mg, and Al in octahedral sites, and also with reduced K-content.

Trioctahedral illites correspond to the dioctahedral varieties, but are much rarer.

The hydrate three-layer silicates swell in water, as a result, increasing interlayer separation from water inhibition. Montmorillonite and saponite belong to the more extensive smectite group of clay minerals. These minerals have lower but relatively constant negative layer charge, resulting in part from tetrahedral substitution of Al, and in part from octahedral substitutions. This negative layer charge is balanced by loosely bonded, exchangeable cations between the layers.

Vermiculite differs from the smectites by its higher layer charge. There is no sharp boundary between the vermiculites and smectites. The layer thickness indicated in table 3 for vermiculite correspond to air-dried material.

For sudoite an ideal formula is given in table 4, which correspond to the chemical composition of kaolinite.

요 약

본문은 광물학 및 습식야금법의 관점에서, 산성용액 내의 점토 광물의 물리적 특성과 화학적 특성을 문헌에 의해 검토한 것이다.

점토광물의 몇가지 중요한 특성은 이들이 산성용액내에서 양이온을 교환하고 흡수팽창하며, 이질광물로 분해(incongruent dissolution)하는 능력을 갖는다는 것이다.

여러 점토광물들은 양이온 교환과정으로 금속 이온들을 용액으로부터 흡착할 수 있다. 일반적으로 이들의 양이온 교환능력은 다음 순서로 증가된다. 즉, kaolinite, halloysite, illite, vermiculite, montmorillonite 산성용액내에서는 점토광물들에 의하여 등과 같은 양이온 흡착은 수소와 알루미늄에 의해 크게 방해될 받으므로, 우라늄 및 동 등의 금속을 회수하는 데는 점토광물이 중요한 요소가 되지 않는다. 그러나, 염기성용액에서는 양이온 흡착(uptake)이 중요하다.

흡수 팽창성은 낮은 pH에서 최소가 된다. 이는 격자 파괴에 기인할 가능성이 많다. 흡수 팽창은 montmorillonite형 점토에서 조절이 되는데 그것은 내부층의 Na 이온이 리튬 과/또는 수산화된 알루미늄 이온과 교환을 하기 때문이다.

점토광물에 대한 산의 효과는 다음과 같다,

i) 표면적 및 다공성이 증가됨에 따라 보다 작은 판상의 집합체로 분리됨

ii) 점토-산 반응은 다음 순서로 일어난다.

⊙ 내부층 양이온들의 H⁺ 치환

⊙ Al, Fe, Mg 등의 팔면체 양이온의 이동.

⊙ 사면체 Al 이온들의 이동.

산의 공격반응(attack)은 점토 입자의 가장자리에서 부터 시작되어 내부로 계속되며, 수화된 규소겔을 가장 자리에 남긴다.

iii) ⊙과 ⊙의 반응속도는 위-일급(pseudo-1st order)이며, 이는 산의 농도에 비례한다. 그리고 그 속도는 온도 매 10°C 증가에 따라 배가된다.

산에 의한 동이나 우라늄을 제자리에서 용해시키는 경우 고찰할 문제는 다음과 같다.

i) 1년 혹은 그 이상의 오랜 작용으로 산의 반응을 받은 점토광물은 규소겔을 남길 것이다. 그런데 이 겔이 용해(leaching)작용을 받고 있는 유용 광물 표면을 덮게 되면 용해에 의한 회수 속도는 실질적으로 감소된다.

ii) 0.5% 점토광물과 동을 함유하는 회수 가능한 동 광상에 대해 점토-산 반응에 사용될 값의 상승은 동

1 파운드당 1.5¢이다. (혹은 구리 1 파운드당 H₂SO₄ 0.93 lbs)

점토광물에 의한 이러한 산의 소모량이 산화동광상에서 동을 추출하는데 경제적 평가의 한 요소가 될 것이다.

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