

## Simultaneous mineralization of CO<sub>2</sub> and recovery of soluble potassium using earth-abundant potassium feldspar

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CO<sub>2</sub> capture and storage (CCS) is an important strategy in combatting anthropogenic climate change. However, commercial application of the CCS technique is currently hampered by its high energy expenditure and costs. To overcome this issue, CO<sub>2</sub> capture and utilization (CCU) is a promising CO<sub>2</sub> disposal method. We, for the first time, developed a promising method to mineralize CO<sub>2</sub> using earth-abundant potassium feldspar in order to effectively reduce CO<sub>2</sub> emissions. Our experiments demonstrate that, after adding calcium chloride hexahydrate as an additive, the K-feldspar can be transformed to Ca-silicates at 800°C, which can easily mineralize CO<sub>2</sub> to form stable calcium carbonate and recover soluble potassium. The conversion of this process reached 84.7%. With further study, the pretreatment temperature can be reduced to 250°C using hydrothermal method by adding the solution of triethanolamine (TEA). The highest conversion can be reached 40.1%. The process of simultaneous mineralization of CO<sub>2</sub> and recovery of soluble potassium can be easily implemented in practice and may provide an economically feasible way to tackle global anthropogenic climate change.

**CCU, mineralization, potassium feldspar, potassium salts, CCS**

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Carbon dioxide (CO<sub>2</sub>), produced from the combustion of fossil minerals, is considered to be one of the main factors responsible for global climate change. CO<sub>2</sub> emission reduction has become a significant issue of common concern worldwide. CO<sub>2</sub> capture and storage (CCS) is currently considered one of the most effective techniques for reducing emissions, maintaining the current atmospheric CO<sub>2</sub> concentration, and alleviating greenhouse gas effects [1,2]. While a number of countries or regions have carried out field demonstration projects related to CO<sub>2</sub> geological storage to test CCS, wide application of the CCS is mainly hampered by its high costs. To alleviate the associated costs, appropriate strategy should be focused on carbon capture

and utilization (CCU) [3–6]. By CCU, we mean CO<sub>2</sub> being captured and used as raw material to produce high-value products (or related by-products) thereby reducing CO<sub>2</sub> emissions. In industry, one of method of utilization of CO<sub>2</sub> is transforming CO<sub>2</sub> into organic chemicals or polymers. Another method was regenerate methanol and hydrocarbon from CO<sub>2</sub> and H<sub>2</sub>O which can be used as fuel. These two methods confronted the problem of high material cost, high energy consuming and short lifetime of product. Therefore, many people considered that the CCU method can only transforming small amount of CO<sub>2</sub>, which has little effect on reducing the emission of CO<sub>2</sub>, and the CCU cannot be regarded as the main CO<sub>2</sub> disposal method.

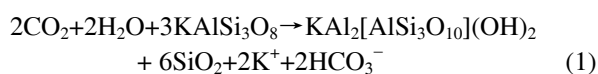
CO<sub>2</sub> mineralization is a relatively new technology in the field of CO<sub>2</sub> geological sequestration [7]. Compared with

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other CCS technologies, it has the advantage of safely storing CO<sub>2</sub> for a very long, if not infinite, time, by converting CO<sub>2</sub> into a solid phase. Through a reaction between rich calcium and magnesium ions in natural alkaline ores [8–18] and alkaline wastes [19–23], CO<sub>2</sub> could be converted into stable solid carbonates, such as magnesium carbonate and calcium carbonate. Forsterite, with a high CO<sub>2</sub> conversion rate, is the main mineralization material. Current research shows that when reacting with CO<sub>2</sub> within a solution of NaCl and NaHCO<sub>3</sub>, at a temperature of 185°C and pressure of 15 MPa, forsterite with a particle size of 37 μm can reach a conversion rate of 81% [1,18]. Unfortunately, forsterite (a magnesium silicate) tends to distribute along either present or ancient continental boundaries [1], and thus are not available in all countries with significant CO<sub>2</sub> emissions, such as China. Thus, it is difficult to obtain low-cost forsterite in many countries or regions important for reducing global CO<sub>2</sub> emission. Neither on-site nor off-site mineralization of CO<sub>2</sub> based on forsterite has been implemented. Seeking rich, low-cost alternative raw materials for CO<sub>2</sub> mineralization, and the means to fulfill high reaction efficiency, low reaction requirements, and easy industrialization, will likely be the future direction of CO<sub>2</sub> mineralization.

Feldspar is one of the most stable and abundant minerals in the earth, accounting for about 60% of the total mass of the earth's crust. Taking the average content of potassium within feldspar of 4% into account, within the scope of human use (about 5 km underground), the reserves of K-feldspar (KAlSi<sub>3</sub>O<sub>8</sub>) is about 95.6 trillion tons. If the K-feldspar were used for mineralization of CO<sub>2</sub> with a conversion rate of 50%, it could theoretically sequester more than 3.82 trillion tons of CO<sub>2</sub>. According to a report by the International Energy Agency [24], global carbon dioxide emission in 2010 was expected to reach 30.06 billion tons. Potentially, in theory the earth's natural potassium feldspar can mineralize as much as 127 years of global CO<sub>2</sub> emissions.

Unfortunately, because of the structural stability of potassium feldspar, the feldspar does not easily react with weakly acidic CO<sub>2</sub>—the reaction progress is given in eq. (1) [1].



Under natural conditions, the reaction between CO<sub>2</sub> and potassium feldspar usually takes hundreds to thousands of years [1,25]. Even after increasing the reaction temperature and the partial pressure of CO<sub>2</sub>, it is still difficult to significantly increase the reaction rate of potassium feldspar with CO<sub>2</sub> [26]. Therefore, meaningful CO<sub>2</sub> mineralization, during the time period of interest for CCS, can barely be achieved by this chemical reaction. So far, there has been neither research nor industrial application of K-feldspar with respect to effective mineralization of CO<sub>2</sub>.

Using earth's natural potassium feldspar to mineralize CO<sub>2</sub> with high efficiency and low cost faces at least two challenges: (1) how to destabilize the stable crystal structure

of potassium feldspar to make it react efficiently with CO<sub>2</sub>; and (2) how to generate a stable mineralization product in nature, since the soluble carbonate generated through the reaction of natural potassium feldspar and CO<sub>2</sub> is easily decomposed. In this study, we use calcium chloride, a common by-product in alkali industry, which currently has limited practical use, to partially deal with these challenges. Resulting from the interaction between calcium and aluminosilicates, calcium chloride may help undermine the structure of potassium feldspar to form relatively active calcium aluminosilicates that react easily with CO<sub>2</sub> to produce stable solid calcium carbonate.

## 1 Experiments

### 1.1 Materials

Feldspar (reddish in color, from Shandong Province, China) was used as a raw material. By crushing and ball-milling the feldspar samples, the feldspar particle sizes reduced to 45 μm. X-ray diffraction (XRD) results indicate that the main mineral composition of feldspar includes microcline (KAlSi<sub>3</sub>O<sub>8</sub>) and Albite (NaAlSi<sub>3</sub>O<sub>8</sub>). Energy dispersive X-ray fluorescence (XRF) analysis shows that the silicon content in the ore is 32.7%, the aluminum content 9.3%, potassium content 8.5%, sodium content 2.5%, calcium content 0.17%, and copper content 0.15%. There are also trace amounts of zinc, iron, phosphorus, and chromium. A. R. grade calcium chloride hexahydrate (CaCl<sub>2</sub>·6H<sub>2</sub>O) and anhydrous calcium chloride (CaCl<sub>2</sub>) was used without further purification. The CO<sub>2</sub> was purchased from Dong Feng (China) with the purity of 99.99%.

### 1.2 CO<sub>2</sub> mineralization procedures

In order to destabilize the structural of K-feldspar, two different pretreatment has been taken to transform K-feldspar to Ca-silicates. In high temperature pretreatment, 2.5 g K-feldspar and 2.5 g calcium chloride hexahydrate were mixed together and heated to 800°C in furnace. After activating 1h at 800°C, the reaction was stopped. The product was putted out and cooled to room temperature, then washed by distilled hot water (80°C) and filtered. The filtrate was diluted to 1 L. The solid was oven-dried at 110°C.

The pretreatment test using low temperature was undertaken in 250 mL autoclave, 2.5 g K-feldspar was added with 75 mL solution, which contain 1.85 mol/L CaCl<sub>2</sub> and 0–1.5 mol/L triethanolamine (TEA). The pretreatment was kept 2 h at 250°C. When the autoclave cooled to room temperature, it was opened, and the suspension was filtered. The filtrate was diluted to 250 mL. The solid was oven-dried at 110°C. As a comparison, another test was done using NaOH instead of TEA. The pH of the solution used in this latter test was about 10.05 and the same as that obtained by adding 1.5 mol/L TEA.

The reaction of mineralization of CO<sub>2</sub> was undertaken in a 250 mL autoclave. After adding the solid from pretreatment and 75 mL distilled water, the autoclave was sealed and heated to the reaction temperature (150°C for high temperature pretreatment and 200°C for low temperature pretreatment). CO<sub>2</sub> was directly added into the solution by gas booster, until the partial pressure of CO<sub>2</sub> goes to 4 MPa. The reaction was going at a specific stirring rate (350 r/min). When the reaction time was elapsed (1 h), the autoclave was cooled to 70°C and depressurized, and opened. The suspension was filtered, and the solid was dried at 110°C.

### 1.3 Analysis of solid phases

The mineralogical composition was determined by X-ray diffraction (XRD). The amount of sequestered CO<sub>2</sub> in product was analyzed by thermal gravimetric analysis system (TG). Samples (10–20 mg) were heated in aluminum oxide ceramic cups under an oxygen atmosphere at 20°C/min. The amount of CO<sub>2</sub> sequestered as calcium carbonate was defined on the basis of its dry weight ( $m_{105^\circ\text{C}}$ ) and the weight loss between 105 and 1000°C ( $\Delta m_{105-1000^\circ\text{C}}$ ):

$$\text{CO}_2 [\text{wt}\%] = (\Delta m_{105-1000^\circ\text{C}} / m_{105^\circ\text{C}}) \times 100. \quad (2)$$

### 1.4 Conversion of K-feldspar

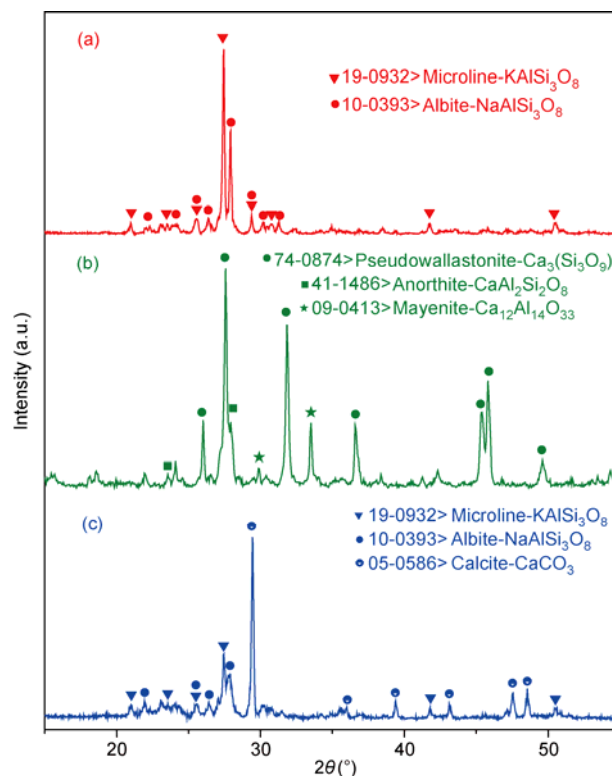
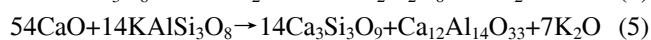
The concentration of K<sup>+</sup> and Al<sup>3+</sup> in solution was tested by ICP (Inductive Coupled Plasma Emission Spectrometer). The conversion rate of K-feldspar  $\zeta$  was defined by comprising the total mass of K in solution  $m_{\text{K}^+}$  with that in the material  $M_{\text{K}}$ , which can be calculated by

$$\zeta = m_{\text{K}^+} / M_{\text{K}}. \quad (3)$$

## 2 Results and discussion

### 2.1 CO<sub>2</sub> mineralization with high temperature pretreatment

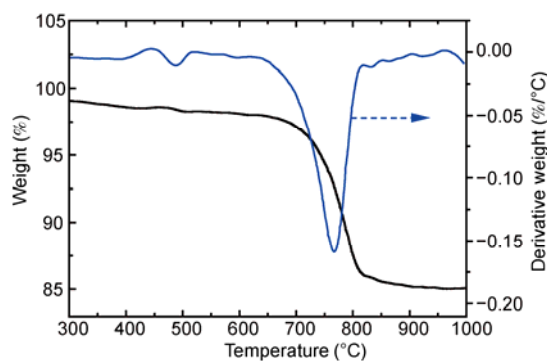
Figure 1 shows the XRD result of mineralogical composition of solids after high temperature pretreatment and mineralization of CO<sub>2</sub>. The experimental results indicate that calcium chloride hexahydrate was decomposed at a high temperature into anhydrous calcium chloride and calcium oxide. Anhydrous calcium chloride and calcium oxide react with potassium feldspar at high temperatures and generate three different calcium silicate salts—pseudo-wollastonite (Ca<sub>3</sub>Si<sub>3</sub>O<sub>9</sub>), anorthite (CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub>) and mayenite (Ca<sub>12</sub>Al<sub>14</sub>O<sub>33</sub>)—that mineralize CO<sub>2</sub> in the form of stable, solid calcium carbonate. These reactions are



**Figure 1** (Color online) XRD results of the reaction (conversion and mineralization) of CO<sub>2</sub> using K-feldspar and calcium chloride hexahydrate at high temperature. (a) Result from natural K-feldspar; (b) result from reaction of K-feldspar and calcium chloride hexahydrate at 800°C; (c) result from the reaction of the conversion production at 800°C and CO<sub>2</sub>.

The result of XRD proved the possibility of simultaneous mineralization of CO<sub>2</sub> and recovery of soluble potassium. The conversion of K-feldspar reached 84.7% after reaction. Figure 2 illustrates the thermogravimetric results of the mineralization production. The content of CO<sub>2</sub> reached 13.15% in product.

Although CO<sub>2</sub> mineralization with high temperature pretreatment showed a good results in activating K-feldspar and mineralizing CO<sub>2</sub>, the pretreatment temperature of 800°C is not desirable, because it corresponds to high energy consumption and therefore high CO<sub>2</sub> emissions. Obviously, converting natural K-feldspar with a higher conversion



**Figure 2** (Color online) Thermogravimetric test results of the conversion product.

rate and lower energy consumption (corresponding to a low required temperature) is the key to developing practically feasible approaches for CO<sub>2</sub> mineralization and cogeneration of soluble potassium salt, using the Earth's natural potassium feldspar.

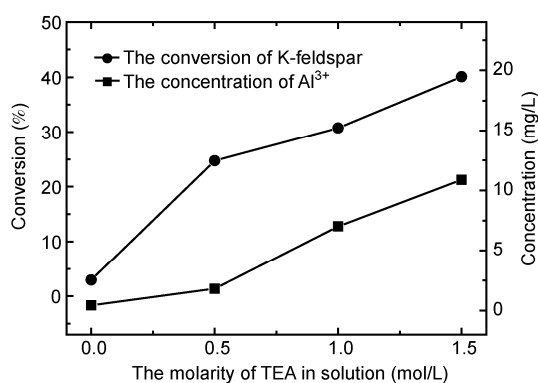
## 2.2 CO<sub>2</sub> mineralization with low temperature

Thermodynamic calculations show that, at 400 K (122.85°C), the  $\Delta G$ , the Gibbs free energy, of reaction (3) is  $-41.3$  kJ/mol [27]. This means that K-feldspar could theoretically convert into anorthite through a reaction with calcium chloride at low temperatures. Previous studies have shown that K-feldspar could react with low-concentrated calcium chloride under hydrothermal conditions with a temperature of 250°C, though with a conversion rate of only 2.1%, this conversion rate is too low for practical applications.

K-feldspar can be dissolved in alkali solution. Casey et al.'s results [29] indicate that the mechanism for alkali-dissolving K-feldspar is as follows: the K-feldspar reacts with OH<sup>-</sup> and generates Al(OH)<sub>4</sub><sup>-</sup> in the solution, and then a poor aluminum-rich-silicon precursor polymer (SiO<sub>2</sub>·*n*H<sub>2</sub>O) is formed on the surface of the K-feldspar to undermine K-feldspar's stable crystal structure, which finally leads to the dissolution of potassium feldspar. A number of experimental results [30–32] have indicated that Al<sup>3+</sup> in the solution controls the dissolution rate of K-feldspar.

Therefore, a compound that could chelate the Al<sup>3+</sup> ion might enhance the conversion of K-feldspar. And this compound should be also stable in relative high temperatures, weakly alkaline, and easy to get. To this end, triethanolamine (TEA) was chosen as a catalyst and calcium chloride as an additive, to convert potassium feldspar and mineralize CO<sub>2</sub> at a relatively low temperature—thereby finding a way to achieve efficient conversion of potassium feldspar to effectively mineralize CO<sub>2</sub> and produce valuable, soluble potassium salt.

Figure 3 illustrates that within the solution with the additive calcium chloride, triethanolamine has a significant promotion effect on the conversion process of potassium feldspar. Without adding TEA, the conversion rate of K-



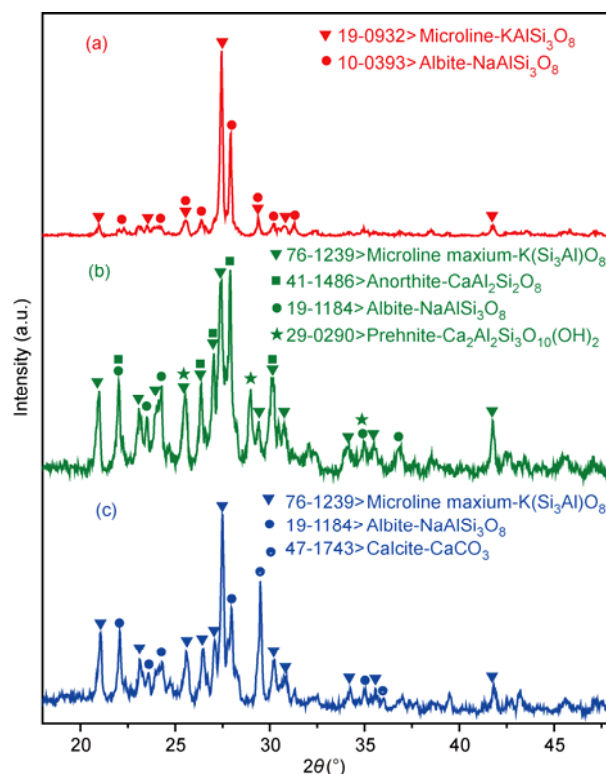
**Figure 3** Effect of triethanolamine TEA concentration on potassium feldspar conversion.

feldspar was only 3%. For a triethanolamine concentration of 1.5 mol/L, the potassium-feldspar conversion rate increased to 40.1%, much higher than that in the comparison test (about 5.1%). The XRD test results have shown (Figure 4) that Si-Al-calcium salt, generated by potassium feldspar under hydrothermal conditions at 250°C, more easily reacts with CO<sub>2</sub> to mineralize CO<sub>2</sub> into stable, solid calcium carbonate.

The conversion rate of K-feldspar increases significantly with increasing concentration of aluminum ions in the solution (Figure 3). This is because in an alkaline solution, Al ions on the surface of the potassium feldspar react with OH<sup>-</sup> to form Al(OH)<sub>4</sub><sup>-</sup> in the solution. Then, Al(OH)<sub>4</sub><sup>-</sup> and TEA together result in chelation that enhances the solubility of Al<sup>3+</sup> within the solution. As a result, more Al ions enter the solution and undermine the stable structure of the potassium feldspar crystals. The additive calcium chloride prompts potassium feldspar's conversion into Si-Al-calcium salt, which more actively reacts with CO<sub>2</sub> and increases the rate of CO<sub>2</sub> mineralization.

## 3 Conclusions

CO<sub>2</sub> capture and utilization (CCU) based on CO<sub>2</sub> mineralization was a new and promising CO<sub>2</sub> sequestration method. Because of the great reserve of natural K-feldspar in earth, it



**Figure 4** (Color online) XRD results of the mineralization of CO<sub>2</sub> by potassium feldspar at low temperature conversion. (a) Results from natural K-feldspar; (b) result from reaction of K-feldspar and calcium chloride at triethanolamine solution with hydrothermal condition of 250°C; (c) result from reaction of the K-feldspar conversion production and CO<sub>2</sub>.

is potential to mineralize plenty of CO<sub>2</sub> and supply valuable soluble potassium salt.

The stable K-feldspar can be activated at 800°C using calcium chloride hexahydrate as additive. After activation, the reactive Ca-silicates were formed and soluble potassium was recovered. The conversion of K-feldspar can be reached 84.7%. CO<sub>2</sub> can be easily reacted with reactive Ca-silicates and sequestered as stable calcium carbonate. The temperature of pretreatment can be reduced to 250°C by adding solution of triethanolamine. At low temperature pretreatment, the highest conversion of K-feldspar can be reached 40.1% using hydrothermal method, which makes it possible to mineralize CO<sub>2</sub> effectively, either *in situ* or based on engineered processes, using the Earth's natural K-feldspar stone. It is also important to emphasize that this technique generates soluble potassium chloride as a value-added product that can be used in the production of potash.

At present, the world's water-soluble potassium mineral resources are unevenly distributed—many countries lack such resources. Take China as an example: its water-soluble potassium salt reserves total 137057500 tons (KCl), only 1 percent of the world's reserves [23]. About half of consumption in China is from imports, leading to a high price for potassium chloride. Therefore, the co-production of soluble potassium salts can significantly compensate for the costs of CO<sub>2</sub> storage in China, and perhaps in other countries as well.

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- 1 Melt B, Davidson O, Connick H D, et al. Report on Carbon Dioxide Capture and Storage. Cambridge: Cambridge University Press, 2005
- 2 Haszedeine R S. Carbon capture and storage: How green can black be? Science, 2009, 325: 1647–1652
- 3 Xie H P. CO<sub>2</sub> storage and climate change (in Chinese). Sci Technol Rev, 2010, 28: 3
- 4 Xie H P. Developing low-carbon technology and promoting green economy (in Chinese). Energy China, 2010, 32: 5–10
- 5 Xie H P. Simultaneous recovery of national resources and mineralization of CO<sub>2</sub>: A new CCU method (in Chinese). Technical Report, Energy and Mining Science, Chinese Academy of Engineering, 2012
- 6 Xie H P, Xie L Z, Wang Y F, et al. CCU: A more feasible and economic strategy than CCS for reducing CO<sub>2</sub> emissions (in Chinese). J Sichuan Univ: Eng Sci. 2012, 44: 1–5
- 7 Seifritz W. CO<sub>2</sub> disposal by means of silicates. Nature, 1990, 345: 486
- 8 Huijgen W J J, Witkamp G J, Comans R N J. Mechanisms of aqueous wollastonite carbonation as a possible CO<sub>2</sub> sequestration process. Chem Eng Sci, 2006, 61: 4242–4251
- 9 Koukouzias N, Gemeni V, Ziocok H J. Sequestration of CO<sub>2</sub> in magnesium silicates, in Western Macedonia, Greece. Int J Miner Process, 2009, 93: 179–186
- 10 Daval D, Martinez I, Corvisier J, et al. Carbonation of Ca-bearing silicates, the case of wollastonite: Experimental investigations and kinetic modeling. Chem Geol, 2009, 265: 63–78
- 11 Valer M M M, Fauth D J, Kuchta M E, et al. Activation of magnesium rich minerals as carbonation feedstock materials for CO<sub>2</sub> sequestration. Fuel Process Technol, 2005, 86: 1627–1645
- 12 Fagerlund J, Teir S, Nduagu E, et al. Carbonation of magnesium silicate mineral using a pressurized gas/solid process. Energy Proc, 2009, 1: 4907–4914
- 13 Kakizawa M, Yamasaki A, Yanagisawa Y. A new CO<sub>2</sub> disposal process via artificial weathering of calcium silicate accelerated by acetic acid. Energy, 2001, 26: 341–354
- 14 Munz A I, Kihle J, Brandvoll O, et al. A continuous process for manufacture of magnesite and silica from olivine, CO<sub>2</sub> and H<sub>2</sub>. Energy Proc, 2009, 1: 4891–4898
- 15 Park A H A, Fan L S. CO<sub>2</sub> mineral sequestration: Physically activated dissolution of serpentine and pH swing process. Chem Eng Sci, 2004, 59: 5241–5247
- 16 Huijgen W J J, Comans R N J, Witkamp G J. Cost evaluation of CO<sub>2</sub> sequestration by aqueous mineral carbonation. Energ Convers Manage, 2007, 48: 1923–1935
- 17 Krevor S C, Lackner K S. Enhancing process kinetics for mineral carbon sequestration. Energy Proc, 2009, 1: 4867–4871
- 18 O'connor W C, Dahlin D C, Rush G E, et al. Carbon dioxide sequestration by direct mineral carbonation: Process mineralogy of feed and products. Miner Metall Process, 2002, 19: 95–101
- 19 Huijgen W J J, Witkamp G J, Comans R N J. Mineral CO<sub>2</sub> sequestration by steel slag carbonation. Environ Sci Technol, 2005, 39: 9676–9682
- 20 Hernandez G M, Lopez R P, Renard F, et al. Mineral sequestration of CO<sub>2</sub> by aqueous carbonation of coal combustion fly-ash. J Hazard Mater, 2009, 161: 1347–1354
- 21 Huntzinger D N, Gierke J S, Sutter L L, et al. Mineral carbonation for carbon sequestration in cement kiln dust from waste piles. J Hazard Mater, 2009, 168: 31–37
- 22 Rendek E, Ducom G, Germain P. Carbon dioxide sequestration in municipal solid waste incinerator (MSWI) bottom ash. J Hazard Mater, 2006, 128: 73–79
- 23 Iizuka A, Fujii M, Yamasaki A, et al. Development of a new CO<sub>2</sub> sequestration process utilizing the carbonation of waste cement. Ind Eng Chem Res, 2004, 43: 7880–7887
- 24 IEA. CO<sub>2</sub> emission from fuel combustion highlights. France: OECD/IEA, 2011
- 25 Xu T, Apps J A, Pruess K. Mineral sequestration of carbon dioxide in a sandstone–shale system. Chem Geol, 2005, 217: 295–318
- 26 Fu Q, Lu P, Konishi H, et al. Coupled alkali-feldspar dissolution and secondary mineral precipitation in batch systems: 1. New experiments at 200°C and 300 bars. Chem Geol, 2009, 258: 125–135
- 27 Ma H W. Potassic Rocks in China (in Chinese). Beijing: Chem Industry Press, 2010
- 28 Liu J, Han Y, Wang Y. Potassium extraction from Potassium-rich shale by high pressure hydrothermal method. Min Metall, 2008, 4: 31–37
- 29 Casey W H, Westrich R, Arnold G W. Surface chemistry of labradorite feldspar reacted with aqueous solutions at pH = 2, 3, and 12. Geochim Cosmochim Acta, 1988, 52: 2795–2806
- 30 Berg A, Banwart S A. Carbon dioxide mediated dissolution of Ca-feldspar: Implications for silicate weathering. Chem Geol, 2000, 163: 25–42
- 31 Oelkers E H, Schott J. Does organic acid adsorption affect alkali-feldspar dissolution rates? Chem Geol, 1998, 151: 235–245
- 32 Blake R E, Walter L M. Effects of organic acids on the dissolution of orthoclase at 80°C and pH 6. Chem Geol, 1996, 132: 91–102