**The technology of CO₂ sequestration by mineral carbonation:
Current status and future prospects**

*F. Wang^a, D. B. Dreisinger^a, M. Jarvis^b, and T. Hitchins^b

^aDepartment of Materials Engineering, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z4

*(*Corresponding author: f.wang@ubc.ca)*

^bHard Creek Nickel Corporation, 203-700 West Pender Street, Vancouver, British Columbia, Canada V6C 1G8

The technology of CO₂ sequestration by mineral carbonation: Current status and future prospects

Abstract

Mineral carbonation (MC) has been extensively researched all over the world since it was found as a natural exothermic process to permanently and safely sequester CO₂. In order to accelerate the natural process, various methods for carbonation of Mg-/Ca-silicate minerals and other industrial wastes have been studied. It has been found that the MC efficiency will increase with an increase of CO₂ pressure, retention time, temperature, mass ratio of Mg or Ca to Si in minerals, specific surface area, and the slurry concentration in a specific range, and with the introduction of effective catalysts, for example, 1M NaCl and 0.64M NaHCO₃ or carbonic anhydrase. However, there still is not a successful industrial application because of high economic cost and slow reaction rate. It is not economic to exploit Mg- and Ca- silicate minerals deposits or tailings to sequester CO₂ by MC, due to the cost of grinding and heat pre-treatment and in some cases the whole sequestration process may result in more CO₂ emissions than the amount of CO₂ sequestered due to the requirements of energy inputs. The process however, may be profitable as a whole (with carbon credits). It is suggested to combine MC with recovery of valuable metals from ore deposits in order to reduce the cost for MC by cost sharing for mineral recovery.

Keywords: CO₂ sequestration; Cost sharing; Metal recovery; Mg silicate minerals; Mineral carbonation

Introduction

According to the reports of the International Panel on Climate Change (IPCC)¹, it is postulated that the global climate is warming. Many of changes which have been observed include the rising of global average sea level, the decreasing of global ice thickness, and the acidification of ocean. All these changes have the potential to affect human health and welfare. As a result of these changes and potential impacts, it may be desirable to control or decrease the CO₂ concentration in atmosphere. Among the available methods, CO₂ removal by sequestration by mineral carbonation is considered as the promising permanent method^{2,3}.

In fact, mineral carbonation (MC) is a natural and exothermic process, which has been observed all over the world⁴⁻⁸. Furthermore, scientists found that Mars also has been experiencing the MC process, through which the CO₂ concentration has been decreased dramatically⁹. In essence, MC process transforms divalent metal oxide or silicate minerals into carbonates. More importantly, the formed carbonates are stable and will not be affected by acid rain^{5,10}. Theoretically, the carbonates can go through the geological period. However, divalent metal oxide is very rare in nature whereas the magnesium- or calcium- silicate minerals are abundant on earth¹¹. Therefore, the main materials for MC are Mg- or Ca-silicate minerals⁶, which in the form of peridotite globally has the carbonation capacity of more than 100 trillion tons CO₂⁸. The following equations (1-4) are the most important and main MC reactions².

However, these natural processes are kinetically unfavourable under atmospheric and pressure conditions though they are thermodynamically favoured⁶. They usually need to take hundreds of years to millennia¹². Since the 1990s^{2,3,6}, the current MC research mainly focuses on how to accelerate this process to an effective and acceptable extent, in order to sequester CO₂. From the originally direct gas-solid MC to current several branches of MC, for example, in-situ gas-aqueous-solid route, ex-situ direct gas-aqueous-solid route, researchers have obtained many significant breakthrough^{2,4-6,12-18}. However, the assignment of CO₂ sequestration by MC is still very urgent. Therefore, it is meaningful to summarize the development of MC and to point out the future directions. It has been certified that direct gas-

solid MC route is extremely slow and cannot be applied effectively^{19–21} while addition of water can considerably enhance the MC rate^{5,20,22,23}. Thus, gas-solid MC routes are excluded in this literature review. By contrast, this review concludes the development, current status and prospects the future of the gas-aqueous-solid MC routes.

MC by Mg- and Ca- silicate minerals

In-situ MC

The Mg- and Ca- silicate minerals which are available for MC are mainly in basalts and peridotite⁸. They are called mafic and ultramafic rocks respectively according to their content of SiO₂, 45-52% and <45% respectively. Both groups of silicate minerals are being researched.

Basalts

Basalts form the top igneous layer in the oceanic crust and occur in large continental provinces, shown in Figure 1. Generally, basalts are more abundant than peridotite.⁸

Thus far, the most successful and the most important in-situ MC by basalts is the CarbFix pilot project in Iceland. This project is a cooperation between Iceland and the United Kingdom (UK), the United States of America (USA), France, Netherlands, Australia and Denmark^{25–27}. A CO₂-H₂S gas mixture was injected into a 2000-m-deep well and monitored the MC situation by 8 monitoring wells ranging in depth from 150 to 1300m, as shown in Figure 2²⁵. During the in-situ MC, the water temperature and pH are in the range from 20°C to 33°C and from 8.4 to 9.4 without oxygen respectively²⁸. Furthermore, in order to prevent the CO₂ gas leakage during injection, they developed a novel CO₂ injection system, dissolving the gas mixture into down-flowing water into the well and keeping the CO₂ concentration below its solubility at these conditions²⁹. Isotopic analysis method is applied to

monitor the MC process. Their study for the first time successfully, thus far, demonstrates that permanently CO₂ sequestration into carbonates through in-situ MC by basaltic rocks is possible and reasonable. They found that 95% CO₂ injected into CarbFix site has been mineralized in just less than 2 years²⁵, rather than hundreds to thousands of years thought before, under these conditions: 20°-33°C, pH=8.4-9.4 with water but without O₂, up to almost 200 bars CO₂ pressure. Thus far, the CarbFix project has successfully sequestered the 175 tons of pure CO₂ and 73 tons of a CO₂-H₂S gas mixture²⁵. Lu et al. also verified that O₂ (up to 3.5% of the mixture gas) has no detrimental effect on MC process³⁰, which means it is unnecessary to use pure CO₂ gas. Based on CarbFix's success, another in-situ MC pilot project, Big Sky Regional Partnership is conducting in Columbia River Basalt in the USA, with the support of CarbFix team (<https://www.or.is/english/carbfix-project>).

However, Hang et al.³¹ had different opinions when they studied a natural CO₂ analogue reservoir (CO₂ gas injected into depleted oil reservoirs³²). They found that there were no obvious MC reaction and carbonates from CO₂ gas were rather limited.

Peridotite

Peridotite has a higher divalent metals content with lower silica content. Theoretically, it has great capacity to permanently store CO₂ and is more suitable for MC than basalts. Peridotite occurs on almost every continent^{8,33}. It is clear that there are a lot of peridotite deposits along the east and west coast of North America. Furthermore, peridotite is more reactive than basalts theoretically³⁴. However, both porosity and permeability of peridotite are very low⁸. These hinder the in-situ MC development and thus the research of in-situ MC by peridotite is still in the infancy stage.

At present, there has been less active in-situ MC by peridotite research³⁵. In fact, in-situ MC by peridotite research still mainly concentrates on passive MC. Kelemen and

Matter^{8,36} have evaluated that MC capacity of Oman site alone is over 30 trillion tons CO₂ and by near Oman surface approximately $\sim 10^3$ tons of CO₂ km³/year are consumed by passive peridotite carbonation. In addition, many researchers⁷ have researched the passive MC on mining tailings and the results are also promising. Lechat et al.³⁷ simulated the in-situ MC for ultramafic milling wastes by laboratory scale experiment. They supposed that the diffusion of CO₂ was the dominant transport mechanism and the MC reaction close to the surface was the most active. In fact, this process should belong to ex-situ MC because the milling wastes are the tailings which had been through previous pulverization and other processing process, rather than the original ores underground.

It is interesting that Schaef et al.³⁸ newly developed in-situ High Pressure X-Ray Diffraction (HXRDX) and in-situ Infrared Spectroscopy (IP) and applied them to in-situ MC studies. With the help of these innovative in-situ analysis methods, the generated nesquehonite, magnesite and calcite due to MC reactions have been identified under the CO₂ pressure (90-160 bars) and temperature (35-70°C). In addition, they observed that carbonation extents of peridotite were correlated to the thicknesses of mineral surface's water-film by in-situ IR and enstatite (MgSiO₃) was the least reactive by in-situ HXRDX.

However, as a whole, there is still no successful in-situ (underground) MC project report thus far. The limits are mainly the decrease of permeability due to clogging or porosity from precipitates and the passivation layers from generated silica. The former limits the practical scale of MC and the latter prevents the further carbonation reaction. Zhang and Liu³⁹ made a review of porosity-permeability relationships in modeling salt precipitation during in-situ MC. According to their review, there is no unequivocal conclusion about whether the permeability or porosity will decrease due to the precipitation of carbonates. Therefore, the in-situ MC way is promising but there are still work which need to be done.

Especially, the success of CarbFix project makes the in-situ MC more promising and more attractive.

Ex-situ direct MC

Thus far, the majority of mineral carbonation technology development still focuses on the ex-situ ways. Since 1990s^{3,13,40–44}, scientists have started the fundamental research on MC by peridotite, in order to accelerate the natural process. At present, the fundamental characteristics of MC have been discovered. It is hard to accelerate the process except for strict conditions, high temperature, high CO₂ pressure and small particle size^{13,23,40,42,44–47}. If the materials are serpentine, heat pre-treatment will be also needed^{40,48}. The reasons why so strict conditions are needed are from three main rate-limiting steps². The first and the most rate-limiting step is the CO₂ dissolution into solution from gas^{2,49,50}, followed by the dissolution of Mg- or Ca- silicate minerals into solution. However, whether the former or the latter limits the extent of MC still remains in controversy^{51,52}. But there is no doubt that both of them are the main difficulties. The less important step is the product layer diffusion, for example the generated MgCO₃ and SiO₂ layers.

Based on the rate-limiting mechanisms, the strict conditions requirement for MC can be easily explained. Firstly, particle size determines the specific surface area which affects the contact between minerals and solution, which controls the dissolution of minerals. So generally, with the particle size increasing, the MC efficiency also increases. Temperature affects the dissolution of both minerals and gas CO₂ into solution. But the influence on them is different. The dissolution of minerals increases with the increasing temperature⁵³ while the dissolution of CO₂ gas decreases⁵⁴. In order to address the conflicts between them, high CO₂ pressure is needed. High CO₂ pressure can improve the dissolution of the CO₂ itself to balance the detrimental effects of high temperature, but also facilitate to increase temperature

over 100°C and enhance the dissolution of minerals⁵³. Furthermore, with MC reaction going, the more and more solid product of carbonates and silica will be produced and cover the surface of unreacted minerals, which hinders the MC reaction from continuing further. Therefore, continuous agitation and high but suitable liquid/solid (L/S) ratio is helpful. They can help remove the passivation layers immediately by attrition function when MC reaction is happening. If the mineral target is serpentine, because serpentine is more stable than olivine as serpentine is weathered from olivine⁴⁸, heat pre-treatment can help remove the –OH group and disintegrate the crystal structure of serpentine and then facilitate to dissolve serpentine into solution.

Typically, the American Albany Research Center (ARC) discovered an effective but economical catalyst, the mixture of NaHCO₃ and NaCl^{13,40,42,44}. The mechanism of catalyst can be presented as the equations (5-7). Bicarbonate ion can react with the Mg- or Ca- silicate minerals to form more insoluble carbonates and hydroxyl ions. In return, the hydroxyl ions can immediately absorb CO₂ gas to form bicarbonate ions again. Furthermore, the chloride ions can form complex ions with magnesium cations, which can facilitate the dissolution of magnesium silicate minerals by increasing the solubility of magnesium. In principle, the additives will not be consumed. In addition, the discovery promotes MC development in basic conditions. Historically the main approach has been to dissolve silicate minerals in acid conditions^{55,56}. The slurry of Mg- or Ca- silicate minerals is weak basic in essence. So the discovery is a great breakthrough for MC. In fact, almost most all later MC researchers are based on or referred to their work including the catalyst.

All these fundamental research not only promotes the development of ex-situ MC but also in-situ MC. However, it is also clear that intensive energy is needed for acceptable MC efficiency and rate, which results in very high costs. It is because of this that there is still no successful ex-situ MC practical application yet. ARC tried to combine ex-situ direct MC with in-situ MC by injecting mineral slurry and CO₂ gas into underground because the ex-situ direct process is too energy-intensive⁴¹. This approach may be promising.

Furthermore, in order to enhance the MC efficiency under mild conditions, lower pressure and lower temperature, considering that grinding by mills is used to not only increase specific surface area of minerals and also disintegrate the structures of minerals to some extent⁵⁷⁻⁶⁵, some researchers started to develop a similar in-situ grinding MC concept which means MC happens during grinding stage. The mechanism of in-situ grinding MC can be explained by Figure 3. Park and Fan⁶⁶ found that in-situ grinding can help remove SiO₂ passivation layers instantly and improve the dissolution of serpentine, especially when there is Mg-leaching solvent in this system. They did the research in a 5 cm diameter fluidized bed reactor, which can be shown in the schematic diagram of Figure 4. Verduyn et al.¹⁸ also presented their idea to make flue gas containing CO₂ start to contact with minerals slurry during grinding stage because of the fact that MC efficiency is much slower by directly using flue gas due to the lower CO₂ pressure than using pure CO₂ gas. They wanted to do this to counteract the negative influence of directly using flue gas (with about 10% CO₂). Turianicová et al.^{57,58,64,67} used a planetary ball mill to do the in-situ grinding MC of vermiculites without additives and verified that this way can indeed enhance the structural breakdown of minerals. However, most of them did not continue to do the in-situ grinding MC research because there are specific requirements for milling equipment, for instance, sealed and higher pressure than atmosphere. These may not only increase investment on

equipment but also risk the whole process because of the importance and high energy consumption of ball mill in a plant. But in-situ grinding MC may be still worth researching.

Particularly, Santos et al.⁶⁸ did an interesting and meaningful research that ex-situ direct MC was used as a pre-treatment to enhance nickel extraction from pure olivine. The olivine they adopted has the nickel content of 0.27%. The majority of nickel exists in this olivine by replacing magnesium in the Mg-silicate structure as the isomorphous Mg-Ni silicate ((Mg,Ni)₂SiO₄) and is dispersed in the materials. Fully carbonation efficiency has been acquired under the conditions: 35 bars CO₂ pressures, 200°C, 20(wt)% slurry concentration, 86% <80µm of particle size, 0.64M NaHCO₃+1M NaCl for 72 hours. They compared the leaching behaviour of nickel between fresh olivine and full carbonated olivine and found that the leaching efficiency was increased dramatically at the same conditions by HCl acid or HNO₃. This shows that carbonation made nickel leaching easier. In fact, after the complete carbonation, nickel was found to be more dispersed by EPMA analysis. This research, for the first time, connects MC tightly with valuable metals. However, after the carbonation, they just leached all the solids. Therefore, CO₂ in the whole process can be shown as CO_{2g}→MgCO_{3s}→CO_{2g}. There is no CO₂ which has been carbonated. That is to say, in terms of CO₂ sequestration, this process is meaningless. But it points out a new idea that it will be more valuable if ex-situ MC could be tightly connected with valuable metal recovery.

Furthermore, many researchers^{6,14,52} believe that the Energy Reactor[©] invented by Innovation Concepts may be the most promising ex-situ direct MC method, as shown in Figure 5(a). Its specialties are that it not only transforms the high CO₂ pressure requirement into gravity itself but also utilizes the heat released from MC reaction itself. The former can decrease the requirements of equipment and reduce the costs considerably. And the latter can make full use of the exothermic characteristic of MC reactions and decrease the requirement

of massive energy input which is limiting the economics of MC. In addition, due to high speed of slurry during the Energy Reactor[®], particles will be attrited, which can remove the passivation layers of silica and facilitate the successive MC reaction. According to the report of Innovation Concepts, the temperature and pressure can be up to 200°C and 90 bars (<http://www.innovationconcepts.eu/CO2EnergyReactor.htm>). However, this process is hard to simulate in a laboratory scale. In the year 2016, there is cooperation between Canada and Netherlands to do lab-scale CO₂ Energy Reactor experiments, as shown in Figure 5(b). Though they believed that the MC through this apparatus was good but it still did not make full use of the specialities of Energy Reactor itself. However, they gave interesting ideas that it is not advisable to obtain maximal MC efficiency by increasing the processing costs and in contrast, the main impetus of MC is the value of products.

In addition, some researchers are trying to find a more efficient catalyst than NaHCO₃+NaCl. One of the catalysts is Carbonic Anhydrase (CA). It is a kind of metalloenzyme, E·ZnH₂O. The mechanism that it enhances MC can be shown in equations (8-12). Compared to the buffer of NaHCO₃+NaCl, it can enhance not only the dissolution of silicate minerals but also the dissolution of CO₂ gas, both of which are the main rate-limiting steps. Power et al.^{49,50,69} used it to accelerate the MC by brucite and verified that CA can help address the rate-limiting step of CO₂ dissolution. However, the price of CA is too expensive, approximately \$800 per 500mg Bovine CA (No. C3934). Therefore, some researchers believed it was impossible to adopt so expensive CA to sequester CO₂², and it is also the main reason why there is almost no research on MC of olivine enhanced by CA. But if the price of CA could be much cheaper and more suitable, for example, artificial CA, MC would have great development.

Ex-situ indirect MC

Ex-situ indirect MC, in fact, dates from the ex-situ direct MC. In order to accelerate the MC rate and address the rate-limiting step of dissolution of minerals, as well as to make MC process profitable by increasing the value of products, some researchers tried to separate the carbonation reaction from the dissolution of Mg-silicate minerals as different stages, though some others believed pressurized reactors are the highest investment costs⁷⁰. At present, the majority of indirect MC is two-stage MC: dissolution of silicate minerals followed by carbonation reaction⁷¹. The mechanism of indirect MC is based on that minerals are dissolved or precipitated on different pH values or different temperatures. But it should be noticed that ex-situ indirect MC does not bypass the requirement of pre-treatments, for example, fine-grinding with/without heat-treat, which mainly result in non-profitable direct MC processes^{72–74}.

Azdarpour et al.⁷⁵ made a review on indirect MC through pH-swing process. Firstly, silicate minerals are dissolved in low-pH solution (with or without ammonium salts), and after L/S separation, carbonates are acquired by raising the solution's pH value⁷³. Compared to direct MC, it is easier to acquire relatively high carbonation efficiency by pH-swing ways. In addition, the carbonates product with high purity also can be acquired, which can considerably increase the value of products. However, MC by pH swing, in general, still cost too much because the minerals prior to dissolution also need to be ground which is the main costs of MC. Furthermore, massive additives will be consumed and it is hard to recycle them. More importantly, this method cannot use the exothermic characteristics of MC.

The representative of institutions who use temperature change to reach the dissolution and carbonation is the Åbo Akademi University in Finland^{5,22,76}. They previously researched the direct gas-solid MC and have done a lot of significant works^{4,5}. Recently, they^{10,12,16,22,76,77} invented the ÅA route which has 3 stages and can be shown in Figure 6. The original idea of this technology is to utilize the exothermic heat from MC. So in the first stage, direct solid-solid reaction between ammonia sulphate and Mg-silicate minerals happens under 400~440°C to generate solids containing MgSO₄. Then in near ambient aqueous solution, precipitation Mg(OH)₂ is acquired and subsequently enters a pressurized fluidized bed under conditions of over 20 bars of CO₂ pressure and 450~500°C to carbonate CO₂. The chemical reactions can be shown in equations (13-15). Generally, the whole process does not need to consume additional energy. But in fact, it is still hard to recover the additive of (NH₄)₂SO₄ and it is very complicated to reach the heat balance including hot-cold-hot alterations. Because of these, they recently changed the final stage (under about 500°C) into aqueous condition (under less than 100°C)²². However, the main two disadvantages still exist.

There is one of interesting ex-situ indirect MC research⁷⁸ It adopted mining wastes for indirect MC through crushing, grinding, transportation, heat-treatment, dissolution and precipitation. Finally, two valuable products can be obtained: magnetic products containing magnetite, and pure carbonates. Through economic evaluation, they believed that the whole process is profitable with carbon credits, and through technical evaluation, they concluded that the whole process needs 1.8252 GJ energy input for sequestering 234 Kg CO₂ by 1 ton rocks. However, if the input energy is from coal combustion, according to the average energy

production value, 6150 kWh/t coal⁷⁹, then the whole process will equivalently produce 260 Kg CO₂ (assuming 85% content of C in coal), which is more than the amount of CO₂ sequestered. According to the emission factor for electricity produced using coal from IPCC report, 760 g CO₂/kWh⁷⁸, the whole MC process will release 385 Kg CO₂, which is still more than the amount of CO₂ it has sequestered. Therefore, though this process may be profitable, it may still be meaningless in terms of CO₂ sequestration.

MC by industrial wastes

Mineral carbonation by industrial wastes is still a significant part of MC to mitigate global warming, though its capacity is much smaller than by natural silicate minerals^{2,6}. Industrial wastes containing divalent metal usually have higher chemical reactivity and their corresponding MC can therefore achieve an acceptable rate of CO₂ conversion under milder conditions^{6,80}. Furthermore, industrial wastes can come from various resources, for example, the coal fly ash (FA)^{20,81–85}, metallurgical slag^{86–89}. Meanwhile, the applied technology is the same as that of MC by silicate minerals.

Mayoral et al.⁸¹ used direct MC route by lime-rich coal ashes. 78% carbonation efficiency can be achieved for coal ash and coal waste under 75°C, pH=11.5, 60mL solution/g ash for only 1 h. Nyambura et al.⁸³ adopted brine and coal FA to sequester CO₂ and found that fractionated coal FA, especially 20-150µm particle size, had the best carbonation efficiency (71.84 kg CO₂/t FA) while larger or smaller size cannot achieve that. Furthermore, brine had the better effect on MC than pure water. Dananjayan et al.²⁰ compared the direct gas-solid MC with direct aqueous MC (L/S ratio of 15) under room temperature, 4 bars for 2h, and found that the dry route is much slower process. By contrast, the aqueous route can obtain the capacity of 50.3 Kg CO₂/t coal FA. Hosseini et al.⁸² adopted indirect MC route to sequester CO₂. In the first stage, coal FC was leached by NH₄Cl solution.

The leachate which containing Mg^{2+} and Ca^{2+} then was used to carbonation by injecting flue gas containing CO_2 to acquire carbonate product which can be sold as a product. The leaching residue also can be sold as a cement additive. During this process, ammonia chloride can be recycled. Theoretically, this process is profitable. Han et al.⁸⁴ also use coal FA to do indirect MC research under room temperature and pressure and found the capacity was up to 31.1 Kg CO_2 /t coal FA. Bertos et al.⁹⁰ also used direct MC route by municipal solid waste (MSW) incinerator ashes not only to sequester CO_2 but also to treat hazardous wastes.

Santos et al.⁸⁷ researched the direct MC by steel slags which were intensified by ultrasound. They also showed that sonication can facilitate the MC reaction by removing the passivation layers of generated carbonates and silica as well as reduce the particle size obviously. Araizi et al.⁹¹ have done the research that the direct MC by three kinds of alkaline waste residues, air pollution control residues, cement bypass dust and ladle slag, were enhanced by ultrasound. They verified that the application of ultrasound can considerably promote the carbonation efficiency but needed the help of high L/S ratios (50-100). Huijgen et al.⁸⁰ also believed that steel slag was suitable for MC. Kasina et al.⁸⁶ tried to use blast furnace and steel making slags to sequester CO_2 through direct MC route. They discovered that steel making slag was much easier to sequester CO_2 into carbonates than blast furnace slag. Su et al.⁸⁸ utilized basic-oxygen furnace (BOF) slag to sequester CO_2 by direct MC as well. However, they acclaimed that BOF slag was a better CO_2 storage medium. Meanwhile, the valuable vanadium and chromium metals were released into solution during MC. Poletini et al.⁸⁹ analyzed in details the effects of particle size on the MC by BOF slag. They found the effect was considerable. Particularly, the carbonation efficiency difference between the particle size of $D_{50}=44\mu m$ and $D_{50}=88\mu m$ was over 60% (approximately 72% and 8% respectively) at the same conditions whereas when $D_{50}=17\mu m$, the carbonation efficiency

decreased to only 44% again. They have the consistent conclusions with Nyambura et al. in terms of the important of particle size.

Song et al.^{92,93} applied flue gas desulfurization (FGD) gypsum for indirect MC to not only sequester CO₂ but gain pure carbonate crystals. Furthermore, Xuan et al.⁹⁴ adopted direct MC to produce eco-friendly concrete blocks by recycling concrete aggregates. They discovered that these concrete blocks got higher strength than normal blocks and CO₂ pressure of 5 bars and retention time of 24 h were enough for the blocks. By comparing the MC between by waste concrete and by anorthosite tailings, Ghacham et al.¹⁹ further showed that MC by waste concrete is much easier than by anorthosite tailings because calcium was locked by the framework structure of anorthosite.

Future prospects

In summary, in the last 30 years, the technology of CO₂ sequestration by mineral carbonation has been developed considerably. Firstly, the fundamental characteristics of MC have been discovered. To acquire high MC efficiency during short period, strict conditions are necessary: high temperature, high CO₂ pressure, fine particle size and catalyst (such as sodium bicarbonate). Otherwise, MC still needs to take long time. Secondly, there has been successful in-situ MC pilot, CarbFix project in basalts in Iceland. It has been verified the possibility of in-situ MC and found that the in-situ MC of basalts only needs to take less than 2 years without any additives rather than hundreds of years. This is a great encouragement for MC further development. Furthermore, in-situ HXRD and in-situ IR technology has been developed and can be used to monitor the practical in-situ MC. In addition, there are also great developments in terms of ex-situ MC: invention of Energy Reactor[®], in-situ grinding MC conception as well as the idea that ex-situ MC can tightly associate with valuable metal recovery.

In the near future, it has been believed that MC technology will undergo rapid development. There will be more in-situ MC of basalts pilots and application in the model function. Whether in-situ MC will be challenged by the decrease of porosity and permeability due to the precipitation of carbonates will also be discovered with the help of in-situ analysis tools and more in-situ pilot research. In-situ active MC of peridotite research will also be promoted.

Ex-situ MC will continue to mainly focus on direct routes but can share the costs with the main flow sheet of valuable metals recovery. Through this way, it will be unnecessary for MC to particularly decrease the particle size of minerals because the valuable metals recovery needs to liberate or expose minerals by grinding as well. Then the majority of costs of ex-situ MC will be decreased dramatically but the profits of the whole process will be increased considerably due to the carbon credits and probable increase of metals recovery. However, it also means that it is not economic to exploit Mg- and Ca- silicate minerals deposits or tailings to only sequester CO₂ by MC⁴⁴, due to the cost of grinding and heat pre-treatment and especially in some cases the whole sequestration process may result in more CO₂ emissions than the amount of CO₂ sequestered due to the requirements of energy inputs though the process may be profitable as a whole (with carbon credits). It is suggested indeed to combine MC with recovery of valuable metals from ore deposits which contain high content of divalent metals. Energy Reactor will play a vital important role in the successful application of ex-situ direct MC owing to its two outstanding advantages: transforming high pressure requirement into gravity and utilizing exothermic heats of MC. In-situ grinding MC may also have positive influence on success of ex-situ MC if the mill equipment which can operate at higher pressure than atmosphere can be made economically. In addition to the mixture of NaHCO₃ and NaCl, more efficient but economical catalysts need to be discovered or manufactured, such as artificial CA. Furthermore, though the capacity of MC by industrial

wastes is much less than by silicate minerals, it is still important, especially if they can make high-value by-products or accompany metals recovery.

References

1. 'Climate Change 2014: Mitigation of Climate Change', 2014.
DOI:10.1017/CBO9781107415416.
2. A. Sanna, M. Uibu, G. Caramanna, R. Kuusik, M. M. Maroto-Valer: 'A review of mineral carbonation technologies to sequester CO₂', Chem. Soc. Rev., 2014, 43, 8049-8080.
3. W. Seifritz: 'CO₂ disposal by means of silicates', Nature, 1990,345(6275), 486.
4. W. Huijgen, R. Comans: 'Carbon dioxide sequestration by mineral carbonation: Literature review update 2003-2004', 2004, ECN-05-022.
5. J. Sipilä, S. Teir, R. Zevenhoven: 'Carbon Dioxide Sequestration by Mineral Carbonation: Literature Review Update 2005–2007', 2008.
DOI:10.1080/00908310600628263.
6. F. J. Doucet: 'Scoping Study on CO₂ Mineralization Technologies', Report No. CGS-2011-007, Pretoria, South Africa, 2011.
7. H. C. Oskierski, B. Z. Dlugogorski, G. Jacobsen: 'Sequestration of atmospheric CO₂ in chrysotile mine tailings of the Woodsreef Asbestos Mine, Australia: Quantitative mineralogy, isotopic fingerprinting and carbonation rates', Chem. Geol., 2013, 358, 156-169.
8. J. M. Matter, P. B. Kelemen: 'Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation', Nat. Geosci., 2009, 2, 837-841.
9. T. Tomkinson, M. R. Lee, D. F. Mark, C. L. Smith: 'Sequestration of Martian CO₂ by mineral carbonation', Nat. Commun., 2013, 4, 2662. DOI:10.1038/ncomms3662.
10. S. Teir, S. Eloneva, C. J. Fogelholm, R. Zevenhoven: 'Stability of calcium carbonate

- and magnesium carbonate in rainwater and nitric acid solutions', *Energy. Convers. Manag.*, 2006, 47(18-19), 3059-3068.
11. P. Renforth, C.L. Washbourne, J. Taylder, D. A. Manning: 'Silicate production and availability for mineral carbonation', *Environ. Sci. Technol.*, 2011, 45, 2035-2041.
 12. R. Zevenhoven, J. Fagerlund: "Fixation of carbon dioxide into inorganic carbonates: The natural and artificial 'weathering of silicates'", Chap. 14, 'Carbon Dioxide as Chemical Feedstock', 353-379, 2010. doi:10.1002/9783527629916.ch14.
 13. D. C. Dahlin, W. K. O'Connor, D. N. Nilsen, G. E. Rush, R. P. Walters, P. C. Turner: 'A method for permanent CO₂ mineral carbonation', 17th Annual International Pittsburgh Coal Conference, September 2000, 1-14. DOE/ARC-2000-012.
 14. A. A. Olajire: 'A review of mineral carbonation technology in sequestration of CO₂', *J. Pet. Sci. Eng.*, 2013, 109, 364-392.
 15. W. J. Huijgen, R. N. Comans: 'Carbon Dioxide Sequestration by Mineral Carbonation: Literature Review', February 2003. ECN-C-03-016.
 16. M. Mazzotti, J. Carlos, R. Allam, K. Lackner, F. Meunier, E. Rubin, J. Sanches, K. Yogo, R. Zevenhoven: 'Mineral carbonation and industrial uses of carbon dioxide'. in 'IPCC Special Report on Carbon Dioxide Capture and Storage', (ed. B. Eliasson and R.T. Sutamihardja), 319-338, 2005.
 17. M. J. Mckelvy, A. V. Chizmeshya, K. Squires, R. W. Carpenter, H. Béarat: 'A novel approach to mineral carbonation: Enhancing carbonation while avoiding mineral pretreatment process cost', November 2006. DOE: DE-FG26-04NT42124.
 18. M. Verduyna, H. Geerlingsa, G. Van-Mossel, S. Vijayakumar: 'Review of the various CO₂ mineralization product forms', *Energy Procedia*, 2011, 4:2885-2892.
 19. A. Ben Ghacham, E. Cecchi, L. C. Pasquier, J. F. Blais, G. Mercier: 'CO₂ sequestration using waste concrete and anorthosite tailings by direct mineral carbonation in gas-

- solid-liquid and gas-solid routes', *J. Environ. Manage.*, 2015, 163, 70-77.
20. R. R. Tamilselvi Dananjayan, P. Kandasamy, R. Andimuthu: 'Direct mineral carbonation of coal fly ash for CO₂ sequestration', *J. Clean. Prod.*, 2016, 112, 4173-4182.
 21. S. Kwon, M. Fan, H. F. DaCosta, A. G. Russell: 'Factors affecting the direct mineralization of CO₂ with olivine', *J. Environ. Sci.*, 2011, 23(8), 1233-1239.
 22. R. Zevenhoven, M. Slotte, J. Åbacka, J. Highfield: 'A comparison of CO₂ mineral sequestration processes involving a dry or wet carbonation step', *Energy*, 2015, 117, 604-611.
 23. A. D. Jacobs: 'Quantifying the mineral carbonation potential of mine waste material: A new parameter for geospatial estimation', PhD thesis, University of British Columbia, Vancouver, BC, Canada, 2008.
 24. E. H. Oelkers, S. R. Gislason, J. Matter: 'Mineral carbonation of CO₂', *Elements*, 2008, 4, 333-337.
 25. J. M. Matter, M. Stute, S. Snæbjörnsdóttir, E. H. Oelkers, S. R. Gislason, E. S. Aradóttir, B. Sigfusson, I. Gunnarsson, H. Sigurdardóttir, E. Gunnlaugsson, G. Axelsson, H. A. Alfredsson, D. Wolff-Boenisch, k. Mesfin, D. Fernandez de la Reguera Taya, J. Hall, K. Dideriksen, W. S. Broecker: 'Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions', *Science*, 2016, 352, (6291), 10-13.
 26. J. Declercq, E. H. Oelkers: 'CarbFix Report: PHREEQC mineral dissolution kinetics database', 2014. CarbFix Project No.281348, WP5-PHREEQC Database.
 27. E. S. Aradóttir, E. L. Sonnenthal, H. Jónsson: 'Development and evaluation of a thermodynamic dataset for phases of interest in CO₂ mineral sequestration in basaltic rocks', *Chem. Geol.*, 2012, 304-305, 26-38.

28. H. A. Alfredsson, E. H. Oelkers, B. S. Hardarsson, H. Franzson, E. Gunnlaugsson, S. R. Gislason: 'The geology and water chemistry of the Hellisheidi, SW-Iceland carbon storage site', *Int. J. Greenh. Gas. Control.*, 2013, 12, 399-418.
29. B. Sigfusson, S. R. Gislason, J. M. Matter, M. Stute, E. Gunnlaugsson, I. Gunnarsson, E. Aradottir, H. Sigurdardottir, K. Mesfin, H. A. Alfredsson, D. Wolff-Boenisch, M. T. Arnarsson, E. H. Oelkers: 'Solving the carbon-dioxide buoyancy challenge: The design and field testing of a dissolved CO₂ injection system', *Int. J. Greenh. Gas. Control.*, 2015, 37, 213-219.
30. J. Lu, P. J. Mickler, J. P. Nicot, C. Yang, R. Darvari: 'Geochemical impact of O₂ impurity in CO₂ stream on carbonate carbon-storage reservoirs', *Int. J. Greenh. Gas. Control.*, 2016, 47, (2), 159-175.
31. S. Hangx, E. Bakker, P. Bertier, G. Nover, A. Busch: 'Chemical–mechanical coupling observed for depleted oil reservoirs subjected to long-term CO₂-exposure –A case study of the Werkendam natural CO₂ analogue field', *Earth Planet. Sci. Lett.*, 2015, 428, 230-242.
32. M. A. Ahmadi, B. Pouladi, T. Barghi: 'Numerical modeling of CO₂ injection scenarios in petroleum reservoirs: Application to CO₂ sequestration and EOR', *J. Nat. Gas. Sci. Eng.*, 2016, 30, 38-49.
33. P. Kelemen: 'Melt extraction from the mantle beneath mid-ocean ridges', *Oceanus*, 1998, 41, (1), 23-28.
34. L. Marini: 'Geological sequestration of carbon dioxide: Thermodynamics, kinetics, and reaction path modeling', 1st edn, Vol. 11, 2007, Elsevier Science.
35. M. C. Dichicco, S. Laurita, M. Paternoster, G. Rizzo, R. Sinisi, G. Mongelli: 'Serpentinite carbonation for CO₂ sequestration in the Southern Apennines: Preliminary study', *Energy Procedia*, 2015, 76, 477-486.

36. P. B. Kelemen, J. Matter: 'In situ carbonation of peridotite for CO₂ storage', Proceedings of the National Academy of Sciences of the United States of America, 2008, 105, (45), 17295-17300.
37. K. Lechat, J. M. Lemieux, J. Molson, G. Beaudoin, R. Hébert: 'Field evidence of CO₂ sequestration by mineral carbonation in ultramafic milling wastes, Thetford Mines, Canada', Int. J. Greenh. Gas. Control., 2016, 47, 110-121.
38. H. T. Schaef, Q. R. Miller, C. J. Thompson, J. S. Loring, M. S. Bowden, B. W. Arey, B. P. McGrail, K. M. Rosso: 'Silicate carbonation in supercritical CO₂ containing dissolved H₂O: An in situ high pressure X-Ray diffraction and infrared spectroscopy study', Energy Procedia, 2013, 37, (509), 5892-5896.
39. S. Zhang, H. H. Liu: 'Porosity-permeability relationships in modeling salt precipitation during CO₂ sequestration: Review of conceptual models and implementation in numerical simulations', Int. J. Greenh. Gas. Control, 2016, 52, 24-31.
40. W. K. O'Connor, D. C. Dahlin, D. N. Nilsen, R. P. Walters, P. C. Turner: 'Carbon dioxide sequestration by direct mineral carbonation with carbonic acid', Proc. 25th Int. Technical Conf. on 'Coal utilization & fuel systems', March 2000. DOE/ARC-2000-008.
41. W. K. O'Connor, G. E. Rush: 'Applications of mineral carbonation to geological sequestration of CO₂', Osti.Gov. 2005. DOE/ARC-2005-010.
42. W. K. O'Connor, D. C. Dahlin, G. E. Rush, S. J. Gerdemann, L. R. Penner, D. N. Nilsen: 'Aqueous mineral carbonation: Mineral availability, pretreatment, reaction parametrics and process studies'. March 2005. DOE/ARC-TR-04-002.
43. L. Penner, W. K. O'Connor, D. C. Dahlin, S. Gerdemann, G. E. Rush: 'Mineral carbonation: Energy costs of pretreatment options and insights gained from flow loop reaction studies', 2004. DOE/ARC-2004-042.

44. S. J. Gerdemann, W. K. O'Connor, D. C. Dahlin, L. R. Penner, H. Rush: 'Ex situ aqueous mineral carbonation', *Environ. Sci. Technol.*, 2007, 41, 2587-2593.
45. W. K. O'Connor, D. C. Dahlin, D. N. Nilsen, G. E. Rush, R. P. Walters, P. C. Turner: 'Carbon dioxide sequestration by direct mineral carbonation: Results from recent studies and current status'.
https://www.netl.doe.gov/publications/proceedings/01/carbon_seq/6c2.pdf
46. L. C. Pasquier, G. Mercier, J. F. Blais, E. Cecchi, S. Kentish: 'Parameters optimization for direct flue gas CO₂ capture and sequestration by aqueous mineral carbonation using activated serpentinite based mining residue', *Appl. Geochemistry*, 2014, 50, 66-73.
47. B. Garcia, V. Beaumont, E. Perfetti, V. Rouchon, D. Blanchet, P. Oger, G. Dromart, A. Y. Huc, F. Haeseler: 'Experiments and geochemical modelling of CO₂ sequestration by olivine: Potential, quantification', *Appl. Geochemistry*, 2010, 25, (9), 1383-1396.
48. N. Koukoulzas, V. Gemeni, H. J. Zioc: 'Sequestration of CO₂ in magnesium silicates, in Western Macedonia, Greece', *Int. J. Miner. Process*, 2009, 93, (2), 179-186.
49. A. L. Harrison, I. M. Power, G. M. Dipple: 'Accelerated carbonation of brucite in mine tailings for carbon sequestration', *Environ. Sci. Technol.*, 2013, 47, 126-134.
50. I. M. Power, A. L. Harrison, G. M. Dipple: 'Accelerating mineral carbonation using carbonic anhydrase', *Environ. Sci. Technol.*, 2016, 50, 2610-2618.
51. D. Daval, R. Hellmann, I. Martinez, S. Gangloff, F. Guyot: 'Lizardite serpentine dissolution kinetics as a function of pH and temperature, including effects of elevated pCO₂', *Chem. Geol.*, 2013, 351, 245-256.
52. R. M. Santos, P. C. Knops, K. L. Rijnsburger, Y. W. Chiang: 'CO₂ Energy Reactor—Integrated mineral carbonation: Perspectives on lab-scale investigation and products valorization', *Front. Energy Res.*, 2016, 4, 1-6.
53. D. E. Giammar, R. G. Bruant, C. A. Peters: 'Forsterite dissolution and magnesite

- precipitation at conditions relevant for deep saline aquifer storage and sequestration of carbon dioxide', *Chem. Geol.*, 2005, 217, 257-276.
54. K. Gilbert, P. C. Bennett, W. Wolfe, T. Zhang, K. D. Romanak: 'CO₂ solubility in aqueous solutions containing Na⁺, Ca²⁺, Cl⁻, SO₄²⁻ and HCO₃⁻: The effects of electrostricted water and ion hydration thermodynamics', *Appl. Geochemistry*, 2016, 67, 59-67.
 55. V. Prigiobbe, M. Hänchen, M. Werner, R. Baciocchi, M. Mazzotti: 'Mineral carbonation process for CO₂ sequestration', *Energy Procedia*, 2009, 1, (1), 4885-4890.
 56. O. S. Pokrovsky, J. Schott: 'Kinetics and mechanism of forsterite dissolution at 25°C and pH from 1 to 12', *Geochim. Cosmochim. Acta*, 2000, 64, (19), 3313-3325.
 57. M. Fabian, M. Shopska, D. Paneva, G. Kadinov, N. Kostova, E. Turianicová, J. Briančin, I. Mitov, R. A. Kleiv, P. Baláž: 'The influence of attrition milling on carbon dioxide sequestration on magnesium-iron silicate', *Miner. Eng.*, 2010, 23, (8), 616-620.
 58. P. Baláž, E. Turianicová, M. Fabián, R. A. Kleiv, J. Briančin, A. Obut: 'Structural changes in olivine (Mg,Fe)₂SiO₄ mechanically activated in high-energy mills', *Int. J. Miner. Process*, 2008, 88, (1-2), 1-6.
 59. T. A. Haug, R. A. Kleiv, I. A. Munz: 'Investigating dissolution of mechanically activated olivine for carbonation purposes', *Appl. Geochemistry*, 2010, 25, (10), 1547-1563.
 60. J. Li, M. Hitch: 'Carbon dioxide adsorption isotherm study on mine waste for integrated CO₂ capture and sequestration processes', *Powder Technol.*, 2016, 291, 408-413.
 61. J. Li, M. Hitch: 'Mechanical activation of ultramafic mine waste rock in dry condition for enhanced mineral carbonation', *Miner. Eng.*, 2016, 95, 1-4.
 62. I. Rigopoulos, K. C. Petallidou, M. A. Vasiliades, A. Delimitis, I. Ioannou, A. M.

- Efstathiou, T. Kyratsi: 'Carbon dioxide storage in olivine basalts: Effect of ball milling process'. Powder Technol., 2015, 273, 220-229.
63. I. Rigopoulos, M. A. Vasiliades, I. Ioannou, A. M. Efstathiou, A. Godelitsas, T. Kyratsi: 'Enhancing the rate of ex situ mineral carbonation in dunites via ball milling', Adv. Powder Technol., 2015, 27, (2), 360-371.
64. E. Turianicová, P. Baláž, L. Tuček, A. Zorkovská, V. Zeleňák, Z. Németh, A. Šatka, J. Kováč, 'A comparison of the reactivity of activated and non-activated olivine with CO₂', Int. J. Miner. Process, 2013, 123, 73-77.
65. R. A. Kleiv, M. Thornhill: 'Mechanical activation of olivine', Miner. Eng., 2006, 19, (4), 340-347.
66. A. H. Park, L. S. Fan: 'CO₂ mineral sequestration: Physically activated dissolution of serpentine and pH swing process', Chem. Eng. Sci., 2004, 59, (22-23), 5241-5247.
67. E. Turianicová, A. Obut, L. Tuček, A. Zorkovská, I. Girgin, P. Baláž, Z. Németh, M. Matik, D. Kupka, 'Interaction of natural and thermally processed vermiculites with gaseous carbon dioxide during mechanical activation', Appl. Clay Sci., 2014, 88-89, 86-91.
68. R. Santos, A. Van Audenaerde, Y. Chiang, R. Iacobescu, P. Knops, T. Van Gerven: 'Nickel extraction from olivine: Effect of carbonation pre-treatment', Metals (Basel), 2015, 5, (3), 1620-1644.
69. I. M. Power, A. L. Harrison, G. M. Dipple, G. Southam: 'Carbon sequestration via carbonic anhydrase facilitated magnesium carbonate precipitation', Int. J. Greenh. Gas Control, 2013, 16, 145-155.
70. I. A. Munz, J. Kihle, Ø. Brandvoll, I. Machenbach, J. W. Carey, T. A. Haug, H. Johansen, N. Eldrup: 'A continuous process for manufacture of magnesite and silica from olivine, CO₂ and H₂O', Energy Procedia, 2009, 1, (1), 4891-4898.

71. N. A. Meyer, J. U. Vögeli, M. Becker, J. L. Broadhurst, D. L. Reid, J. P. Franzidis: 'Mineral carbonation of PGM mine tailings for CO₂ storage in South Africa: A case study', *Miner. Eng.*, 2014, 59, 45-51.
72. N. Kemache, L. C. Pasquier, I. Mouedhen, E. Cecchi, J. F. Blais, G. Mercier: 'Aqueous mineral carbonation of serpentinite on a pilot scale: The effect of liquid recirculation on CO₂ sequestration and carbonate precipitation', *Appl. Geochemistry*, 2016, 67, 21-29.
73. A. Sanna, M. Dri, M. Maroto-Valer: 'Carbon dioxide capture and storage by pH swing aqueous mineralisation using a mixture of ammonium salts and antigorite source', *Fuel*, 2013, 114, 153-161.
74. A. Sanna, X. Wang, A. Lacinska, M. Styles, T. Paulson, M. Maroto-Valer: 'Enhancing Mg extraction from lizardite-rich serpentine for CO₂ mineral sequestration', *Miner. Eng.*, 2013, 49, 135-144.
75. A. Azdarpour, M. Asadullah, E. Mohammadian, H. Hamidi, R. Junin, M. A. Karai: 'A review on carbon dioxide mineral carbonation through pH-swing process', *Chem. Eng. J.*, 2015, 279, 615-630.
76. I. S. Romão, L. M. Gando-Ferreira, M. M. Da Silva, R. Zevenhoven: 'CO₂ sequestration with serpentinite and metaperidotite from Northeast Portugal', *Miner. Eng.*, 2016, 94, 104-114.
77. R. Zevenhoven, J. Fagerlund: 'Mineral sequestration for CCS in Finland and abroad', *World Renewable Energy Congress 2011-Sweden, Climate Change Issues (CC)*, Linköping, Sweden, 2011, 660-667.
78. L. C. Pasquier, G. Mercier, J. F. Blais, E. Cecchi, S. Kentish: 'Technical & economic evaluation of a mineral carbonation process using southern Québec mining wastes for CO₂ sequestration of raw flue gas with by-product recovery', *Int. J. Greenh. Gas*

- Control, 2016, 50, 147-157.
79. A. Gabbard: 'Coal combustion: Nuclear resource or danger'. ORNL Rev., 1993, 26, (3), 1-9.
 80. W. Huijgen, G. J. Witkamp, R. Comans: 'Mineral CO₂ sequestration in alkaline solid residues', Proc. 7th Int. Conf. on 'Greenhouse Gas Control Technologies', Vancouver, Canada, September 2004, ECN-RX-04-079.
 81. M. C. Mayoral, J. M. Andrés, M. P. Gimeno: 'Optimization of mineral carbonation process for CO₂ sequestration by lime-rich coal ashes', Fuel, 2013, 106, 448-454.
 82. T. Hosseini, N. Haque, C. Selomulya, L. Zhang: 'Mineral carbonation of Victorian brown coal fly ash using regenerative ammonium chloride-Process simulation and techno-economic analysis', Appl. Energy, 2016, 175, 54-68.
 83. M. G. Nyambura, G. W. Mugeru, P. L. Felicia, N. P. Gathura: 'Carbonation of brine impacted fractionated coal fly ash: Implications for CO₂ sequestration', J. Environ. Manage., 2011, 92, (3), 655-664.
 84. S. J. Han, H. J. Im, J. H. Wee: 'Leaching and indirect mineral carbonation performance of coal fly ash-water solution system', Appl. Energy, 2015, 142, 274-282.
 85. B. Reynolds, K. J. Reddy, M. D. Argyle: 'Field application of accelerated mineral carbonation', Minerals. 2014, 4, 191-207.
 86. M. Kasina, P. R. Kowalski, M. Michalik: 'Mineral carbonation of metallurgical slags', Mineralogia, 2014, 45, (1-2), 27-45.
 87. R. M. Santos, D. François, G. Mertens, J. Elsen, T. V. Gerven, 'Ultrasound-intensified mineral carbonation', Appl. Therm. Eng., 2013, 57, 154-163.
 88. T. H. Su, H. J. Yang, Y. H. Shau, E. Takazawa, Y. C. Lee: 'CO₂ sequestration utilizing basic-oxygen furnace slag: Controlling factors, reaction mechanisms and V-Cr concerns', J. Environ. Sci., 2016, 41, 99-111.

89. A. Polettini, R. Pomi, A. Stramazzo: 'Carbon sequestration through accelerated carbonation of BOF slag: Influence of particle size characteristics', Chem. Eng. J., 2016, 298, 26-35.
90. M. Fernández Bertos, X. Li, S. J. Simons, C. D. Hills, P. J. Carey: 'Investigation of accelerated carbonation for the stabilisation of MSW incinerator ashes and the sequestration of CO₂', Green. Chem., 2004, 6, (8), 428-436.
91. P. K. Araizi, C. D. Hills, A. Maries, P. J. Gunning, D. S. Wray: 'Enhancement of accelerated carbonation of alkaline waste residues by ultrasound', Waste Manag., 2016, 50, 121-129.
92. K. Song, W. Kim, S. Park, J. H. Bang, C. W. Jeon, J. W. Ahn: 'Effect of polyacrylic acid on direct aqueous mineral carbonation of flue gas desulfurization gypsum', Chem. Eng. J., 2016, 301, 51-57.
93. K. Song, W. Kim, J. H. Bang, S. Park, C. W. Jeon: 'Polymorphs of pure calcium carbonate prepared by the mineral carbonation of flue gas desulfurization gypsum', Mater. Des., 2015, 83, 308-313.
94. D. Xuan, B. Zhan, C. S. Poon: 'Development of a new generation of eco-friendly concrete blocks by accelerated mineral carbonation'. J. Clean. Prod., 2016, 133, 1235-1241.

Figure 1. Locations of continental basalts that could serve as in-situ mineral carbonation sites²⁴

Figure 2. Geological cross-section of the CarbFix injection site²⁵

Figure 3. Mechanism depiction of in-situ grinding direct aqueous mineral carbonation

Figure 4. Schematic diagram of the internal grinding system⁶⁶

Figure 5. (a) Schematic representation of the CO₂ Energy Reactor^{©6} and (b) Lab-scale Energy Reactor: “rocking autoclave” at ~45° position⁵²

Figure 6. Schematic representation of the typical ÅA route (AS: $(\text{NH}_4)_2\text{SO}_4$)⁷⁷