ABSTRACT Removal and long-term storage of the greenhouse gas CO₂ from flue gases from fossil fuel-fired power plants and utilities may be accomplished by mineral carbonation. Since vast resources of suitable magnesium-based minerals silicates such as serpentine (Mg₃Si₂O₅(OH)₄) appear to exist in Finland, this option could support Finland’s commitments under the 1997 Kyoto Protocol. This paper assesses direct, dry mineral carbonation for CO₂ sequestration. Finland’s mineral resources and their quality are discussed, and chemical kinetics studies addressing the influence of gas composition, mineral composition and catalysts are reported. Finally, some practical implications of CO₂ sequestration by mineral carbonation are addressed.

Key words: carbon dioxide, emission reduction, reaction kinetics, geochemistry, ultramafic rocks, Finland, waste disposal.

1. INTRODUCTION

Finland currently generates ~55% of its heat and power from fossil fuels (including peat). Although Finland is slowly shifting its fuel consumption to renewable fuels like wood and waste-derived fuels, there still is a legitimate demand for more base-load energy which can be covered only by additional nuclear power or increased use of carbon-based fuel (fossil and non-fossil). This will give increased CO₂ emissions in the near future, making it difficult to fulfill Finland’s commitments considering CO₂ emissions put down in international agreements. At present, global emissions of CO₂ are at levels above 19 gigatons per annum [1], which is the most significant quantity of the greenhouse gas emissions to the atmosphere, responsible for approx. 60% of the enhanced greenhouse effect. The problem could be partly solved by CO₂ sequestration, i.e. the removal of CO₂ from flue gases followed by long-term storage. The only option for Finland appears to be mineral carbonation, because Finland doesn’t have deep oceans or exhausted oil or gas fields, and improved forestry, biofixation and the utilization of CO₂ do not have enough capacity.
For mineral carbonation the use of magnesium-based silicates, $x\text{MgO} \cdot y\text{SiO}_2 \cdot z\text{H}_2\text{O}$ is favoured because they are available in huge amounts worldwide. These natural resources may be capable of binding all fossil fuel-bound carbon [2,3]. Magnesium silicates can be divided into several subgroups. The largest quantities are olivine, $(\text{Mg,Fe})\text{SiO}_4$, and serpentine, $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$; some other suitable minerals exist in smaller amounts. The chemistry of $\text{CO}_2$ fixation can be summarised as

$$x\text{MgO} \cdot y\text{SiO}_2 \cdot z\text{H}_2\text{O} (s) \Rightarrow x\text{MgO} (s) + y\text{SiO}_2 (s) + z\text{H}_2\text{O} \quad (R1)$$

$$\text{MgO} (s) + \text{CO}_2 \Rightarrow \text{MgCO}_3 (s) \quad (R2)$$

The overall carbonation reaction (R1+R2) is exothermal: the heat effect is +64 kJ/mol and +90 kJ/mol MgCO$_3$, for serpentine and olivine/forsterite, respectively. This may be compared with the heat of combustion of 394 kJ that is realised in the formation of 1 mol of CO$_2$ from carbon. Large-scale flue gas CO$_2$ sequestration as mineral carbonates will, however, require enormous amounts of mineral. For a typical power plant, the mass flows of fuel and carbonated mineral will be of the same order of magnitude: 1 kg of CO$_2$ may require 2 kg of serpentine for disposal: serpentine, for example, contains ~30 %-wt bound MgO.

Only a few laboratories are looking for technical solutions to perform the carbonization of magnesium with carbon dioxide on a large scale. Most important results are reported from the USA, i.e. Los Alamos National Laboratory (NM), Albany Research Center at Albany (OR) and Arizona State University at Tempe (AZ) [2-6]. Whilst the research in the USA is concentrating increasingly on wet methods, using aqueous solutions, the research started in August 2000 at the Helsinki University of Technology (still) aims at dry methods. Two issues must be resolved to make this approach more attractive, as also concluded in a recent feasibility study from the UK [7]:

- extracting the reactive component MgO from the mineral (reaction R1), thereby reducing the mass streams that have to be handled (at e.g. a power plant), and
- speeding-up the kinetics of reaction (R2), which has to take place at temperatures below 300-400°C (and at elevated pressures).

The objectives of our studies at the Helsinki University of Technology, from which some results are reported hereafter, are:

- to optimise the chemistry of direct, dry, magnesium silicate mineral carbonation, addressing process conditions, flue gas composition and the use of catalysts, which involves tests in a (pressurised) thermogravimetric analyser; and
- to analyse practical implications of large-scale application of mineral carbonation for CO$_2$ sequestration such as a detailed mapping of Finland’s magnesium silicate mineral resources and the quality of these minerals, plus the issue of carbonated mineral disposal, and
- to assess the economy of CO$_2$ sequestration by mineral carbonation, considering the type and size of fossil fuel-fired power plant and whether to transport mineral or CO$_2$.

This paper concerns mainly the kinetics studies, plus some words on Finnish mineral resources and the practical implications of a large-scale process for CO$_2$ sequestration at power plants or steel works.
2. MAGNESIUM OXIDE – CONTAINING MINERALS IN FINLAND

Magnesium silicates are often a base component of ores mined for metals like nickel or gold, and usually exist in mixtures of different silicates [8]. In Finland there are many mining activities, mainly mining for metals (nickel, copper), although also talc and limestone are mined. There are 15 major active mines in Finland of which 9 are found in areas with rich magnesium silicate deposits. For example, at the Hitura mine in northern Finland 720000 tons of ore are mined per year, containing 3500 tons of nickel. 4~5% of the ore is pure serpentine or serpentinite, which is a mixture of mainly serpentine, talc and sand [9].

A mapping of so-called ultramafic mineral, *i.e.* magnesium oxide rich deposits in Finland is shown in Figure 1 [10]. The typical age of these deposits is approx. 1900 million years. Unfortunately, very local “spots” such as the deposit of serpentinite at Hitura estimated at 100 million m³ are not shown [11]. Assuming an average depth of the ultramafic rock beds of 50 m, each area of 1 km² marked in the map corresponds to 50 million m³ of potentially useful deposit. This is a very rough estimation that should be used cautiously.

3. MAGNESIUM OXIDE-BASED MINERAL CARBONATION

3.1 Magnesium-based Mineral Carbonation Thermodynamics

The thermodynamics of magnesium silicate carbonation (R1 and R2) shows that, depending on the partial pressure of CO₂, temperatures of the order 200-400°C are preferable. Moreover, the process will benefit from elevated pressures [2, 12-14]. This says, however, nothing about chemical reaction kinetics. MgO may be separated from serpentine at temperatures above 900°C; higher temperatures are needed for olivine. For a large scale pulverised coal-fired power plant one approach could be to inject serpentine into the upper furnace, where the temperature is sufficient to release MgO, followed by carbonation of the MgO (reaction R2) at lower temperatures downstream.
3.2 Magnesium-based Mineral Carbonation Reaction Kinetics

Data on the chemical reaction rate of the carbonation of magnesium-based minerals is scarce. The team from the USA reported reaction rates such as 40-50% conversion after 24 h at 150-250°C, 85-125 bar, with olivine particles of 75-100 µm, in 1998 [4,5]. More recent achievements using wet systems report 65% conversion after 1 hour, mainly as a result of careful control of solution chemistry [5,6].

To get some indication of the quality and reactivity of Finnish magnesium carbonates, a few experiments were conducted using a serpentine that was mined near Kittilä north of Rovaniemi, Finland. Chemical analysis showed that this mineral is quite pure, the contents of Mg and Si being 99.9% and 89.1%, respectively, of the theoretical value for serpentine. However, the mineral contains also 4.4 %-%wt carbonate (carbon bound as CO$_3$). Because of the amount of Mg in the mineral, it was assumed that this carbonate fraction is present as MgCO$_3$, which implies that the “serpentine” is composed of 6.2 %-%wt MgCO$_3$ and 93.8 %-%wt Mg$_3$Si$_2$O$_9$H$_4$. Later, a calcium content of 0.69 %-%wt was measured.

After the tests with the serpentine further tests were being made with a 99.7 %-%wt pure Mg(OH)$_2$ sample provided by Partek Nordkalk Oy.

### Table 2 Chemical analysis of the serpentine and magnesium hydroxide

<table>
<thead>
<tr>
<th>%-wt, dry</th>
<th>Mg(OH)$_2$</th>
<th>Mg</th>
<th>Si</th>
<th>CO$_3$</th>
<th>Ca</th>
<th>MgO</th>
<th>SiO$_2$</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serpentine</td>
<td>26.3</td>
<td>18.1</td>
<td>4.41</td>
<td>0.69</td>
<td>43.6</td>
<td>38.7</td>
<td>12.6*</td>
<td>**</td>
</tr>
<tr>
<td>Mg(OH)$_2$</td>
<td>99.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
</tr>
</tbody>
</table>

* Assuming all Mg as MgO, all Si as SiO$_2$  ** Pure serpentine contains ~ 13 %-%wt bound H$_2$O

3.2.1 Experiments with Serpentine at Constant Temperature

Fine powdered samples (average particle size approx. 50 µm) were carbonated in a pressurised thermogravimetric analyser (PTGA). In this first set of tests, at 200°C, no detectable carbonation was measured after 3 hours, at 1 bar in N$_2$/CO$_2$ 85/15 %-%vol and in N$_2$/CO$_2$/H$_2$O 80/15/5 %-%vol, nor at 15 bar in a N$_2$/CO$_2$ 85/15 %-%vol gas mixture. The final CO$_3$ content of the samples was approx. 4.3 %-%wt, from which it can be concluded that nothing had happened to the samples [12].

3.2.2 Experiments with Serpentine at Increasing/Decreasing Temperature

A second set of tests aimed at “setting free” the active component MgO from the mineral at elevated temperature, followed by carbonation at lower temperatures. For this purpose a serpentine sample was heated at 50 °C/min to 1000°C, followed (after 10 minutes) by cooling at 10°C/min to 200°C, in the PTGA in a N$_2$/CO$_2$ 85/15 %-%vol gas atmosphere. The results shown in Figure 2 (corrected for buoyancy effects) indicates a mass loss during heat-up which corresponds to ~110% of the water and magnesium-bound carbonate in the serpentine [12-14]. Apparently this is due to the release of bound CO$_2$ but other than MgCO$_3$ present in the serpentine mineral. Therefore the serpentine was analysed for Ca as well, since CaCO$_3$ may be present. The analysis result of 0.69 %-%wt Ca in the mineral does not explain the mass loss during heat-up. During the cool-down stage a sudden increase of sample mass is seen near 700°C, followed by a slow increase in CO$_2$ uptake by
MgO up to approx. 0.8 % MgO conversion. The mass fraction of carbon bound as CO$_3$ in the final product was analysed to be 0.5 %-wt (which is lower than in the starting material $\otimes$).

Clearly, more work is needed to obtain a better understanding of the processes taking place during these tests (such as the sudden increase in CO$_2$ uptake at near 700$^\circ$C in Figure 2). This includes especially a more detailed analysis of the magnesium silicate minerals, also in order to get insight into the (possibly catalytic) effects of contaminations.

3.2.3 Experiments with Magnesium Hydroxide at Increasing/Decreasing Temperature

A third set of tests was conducted with a rather pure Mg(OH)$_2$ (average particle size approx. 20 $\mu$m) aiming at studying the effect of the presence of water and/or oxygen in the gas, besides carbon dioxides and nitrogen. These four tests involved heat up at 50 $^\circ$C/min to 1000$^\circ$C, followed, after 10 minutes, by cooling at 10$^\circ$C/min to 200$^\circ$C, at 1 bar, in a 1) an N$_2$/CO$_2$ 85/15 %-vol gas atmosphere, 2) in N$_2$/CO$_2$/H$_2$O 80/15/5 %-vol, 3) in N$_2$/CO$_2$/O$_2$ 80/15/5 %-vol, and 4) in N$_2$/CO$_2$/H$_2$O/O$_2$ 75/15/5/5 %-vol. The results of the cooling, i.e., carbonation stage are given in Figure 3.

Despite the fluctuations in the P-TGA signals, all cases show an increasing conversion of MgO to MgCO$_3$ at an increasing rate when the temperature sinks below approx. 300$^\circ$C. With a gas containing CO$_2$, N$_2$, O$_2$ and H$_2$O an unexpected sudden decrease in the sample mass is seen in the temperature range 750-500$^\circ$C. A clear catalytic effect of water on the carbonation reaction is seen: in fact the highest MgO conversion was obtained with a gas containing CO$_2$, N$_2$, and H$_2$O. A clear influence, if any, of the presence of oxygen, could not be deduced from these results.
For the rate of the carbonation reaction between MgO and CO\(_2\) (R2) a kinetic model can be set up:

\[
-d\frac{m_{\text{MgO}}}{dt} = k_+ m_{\text{MgO}} \cdot p_{\text{CO}_2} - k_- m_{\text{MgCO}_3} = m_{\text{MgO, start}} \frac{dX}{dt}
\]

where \(m\) represents mass (kg), \(t\) is time (s), \(k_+\) and \(k_-\) are the kinetic rate constants for the forward and backwards reactions, respectively (units bar\(^{-1}\)s\(^{-1}\) and s\(^{-1}\), respectively), \(p_{\text{CO}_2}\) is the partial pressure of CO\(_2\) (bar) and \(X\) is the fractional conversion of MgO to MgCO\(_3\) (-). It is noted that the equilibrium constant, \(K_p\), for reaction (R2) equals the ratio

\[
K_p = \frac{k_+}{k_-}
\]

which can be modelled (with temperature \(T\) in K) as:

\[
\ln K_p = \frac{11839}{T} - 20,219 = - \ln p_{\text{CO}_2, \text{equilibrium}}
\]

Using this, equation (1) can be rewritten into a function of forward rate constant \(k_+\), related to the change of conversion \(X\) with temperature \(T\), \(dX/dT\):

\[
k_+ = \frac{\beta}{(1 - X) p_{\text{CO}_2}} \frac{dX}{dt} = k_0 \cdot e^{\frac{-E_{\text{act}}}{RT}}
\]

where \(Z\) is the molar mass ratio \(M_{\text{MgCO}_3}/M_{\text{MgO}} = 2.0918\) and \(\beta\) is the heating (or cooling) rate (K/s). From this the Arrhenius constant parameters \(k_0\) and \(E_{\text{act}}\) may eventually be calculated.

Applying this procedure to the results shown in Figure 3 gives the rate constants as plotted in Figure 4. It is clearly seen that above about 350°C (662°F) the rate decreases with increasing temperature as a result of unfavourable thermodynamics \((\text{viz. equation 2})\), whilst a rate that increases with temperature is seen for lower temperatures. This “turn-over” temperature may be the preferable temperature for mineral carbonation (for this sorbent material !) at 1 bar, and is slightly effected by the composition of the gas phase.
A fourth set of tests, also conducted with the Mg(OH)$_2$ involved heat up at 50 °C/min to 1000 °C, followed, after 10 minutes, by cooling at 10 °C/min to 100 °C, in a N$_2$/CO$_2$ 85/15 %-vol gas atmosphere, at 1 bar. Also, the Mg(OH)$_2$ was mixed with 1%-wt of NaCl, NaHCO$_3$ or Al$_2$O$_3$, respectively, as to investigate any catalytic effect of these. A last test involved the effect of 500 ppm-vol SO$_2$ (to be exact: 488 ppm-vol) in a N$_2$/CO$_2$ gas mixture on the reaction with Mg(OH)$_2$. The results of the carbonation stage of the tests are summarised in Figure 5.

A first finding was that the efficiency of the calcination of the Mg(OH)$_2$ to MgO, which reached almost 99 % for the test with pure Mg(OH)$_2$ at the end of the heat-up to 1000 °C, was not so high when other species were present. For a 99%-wt Mg(OH)$_2$/1%-wt NaCl sample, the conversion efficiency of Mg(OH)$_2$ to MgO was reduced to 94 %, with 1%-wt Al$_2$O$_3$ to 90 %, and with 1 % NaHCO$_3$ to 94 %. With the SO$_2$ present in the CO$_2$/N$_2$ mixture, the conversion efficiency of Mg(OH)$_2$ to MgO was only 88 %. It may be that the calcination reaction is slowed down by the presence of additional species, which may explain some of the results in Figure 5: apparently the calcination is still ongoing during the cool-down stage, giving a mass loss that exceeds the mass gain that would result from carbonation.

Some additional information was obtained with chemical equilibrium calculations (using the HSC-4 free energy minimisation software [15]), suggesting that the NaCl and NaHCO$_3$ may be completely volatilised and lost to the gas phase, whilst no such effect is to be expected with Al$_2$O$_3$. In all cases, MgO is the most stable Mg species, with only traces of MgSO$_4$ in presence of SO$_2$.

In Figure 5, the result with pure Mg(OH)$_2$ shows oscillating behaviour, with only at temperatures below 300 °C a continuously increasing trend: all perfectly according to the thermodynamics for
reaction (R2). With some SO$_2$ present in the gas, a rapid increase to 1 % MgO carbonation is found which below 800°C starts to decrease again. This may be due to the presence of MgSO$_4$, which apparently is carbonated to MgCO$_3$ more rapidly than MgO. The reason for the decreasing lines (until below 200°C) found when some NaCl, NaHCO$_3$ or Al$_2$O$_3$ is mixed with the Mg(OH)$_2$ is totally unclear. This may be due to delayed calcination of the Mg(OH)$_2$, i.e. this still continues when the temperature is decreasing again, since chemical equilibrium calculations do not indicate that species are formed that result in a mass decrease upon reaction with CO$_2$. Clearly, more work and detailed analyses are needed here.

### 3.2.4 Experiments with Serpentine and Magnesium Hydroxide at Elevated Pressures

Besides the experiment with serpentine at 200°C/20 bar mentioned in section 3.2.1, both the serpentine and the Mg(OH)$_2$ samples were tested under heat-up (50 K/min, until 1000°C) followed by cool-down (10 K/min) conditions at pressurised conditions. The results of this fifth set of tests are shown in Figure 6. Repeating the experiment shown in Figure 2, for serpentine, at 15 bar and analysing the solid residue afterwards showed a final CO$_2$ content of approx. 0.8 %-wt [13], which is higher than the 0.5 %-wt obtained at 1 bar. The experiment with Mg(OH)$_2$ was made at 20 bar.

In Figure 6 a negative water release suggests that actually, until about 700°C a mass increase is taking place. What is really taking place may be mineral carbonation, although the 200°C/ 15 bar test with serpentine showed a negligible carbonation effect. Also, during the cool-down stage the mass of the sample continues to decrease, resulting in the curves shown for CO$_2$ uptake in Figure 6. Due to the unexpected outcome of the heat-up stage the composition of the sample at the beginning of the cool-down stage is largely unknown, which explains the shape and final values of the curves for CO$_2$ uptake.
4 PRACTICAL IMPLICATIONS

4.1 Disposal and Use of Carbonated Magnesium-based Minerals

For the carbonation reaction (R2), and its thermodynamic equilibrium constant $K_p$ approximated by equation (2) we find that (at 1 bar) $K_p$ is greater than unity for air containing 400 ppm-vol CO$_2$ at temperatures below ~ 150°C. It means that the product is thermodynamically stable, and more stable than CO$_2$ also, under ambient conditions. It allows for permanent storage space for CO$_2$, whilst the carbonates are environmentally inert and non-toxic [16]. There are huge world deposits of natural magnesite (MgCO$_3$) in the order of 8600 million metric tonnes [17] which have not posed any threat to the environment. The Ministry of Environment in Finland also confirmed that the product magnesium carbonate is not listed as a hazardous waste (Ministry of the Social Affairs and Health Decree 624/2001). Hence, this can be treated as an ordinary waste [18] and it can be used in other applications for which the product is suitable.

The use of (cleaned) magnesite has been documented in many sectors including, as filler materials for paint, paper and plastics, brick manufacturing, fertilizer production, ceramics, and also as a fire retardant [17]. Hence, it is necessary to find out how clean the magnesite product from a CO$_2$ sequestration process will be, which will determine its further use as a raw material. It is quite promising that serpentine waste and tailings can be used, for example, to produce magnesium metal. This approach is followed, for example, by the Magnola Magnesium Plant located in Danville (Quebec), Canada, where over 50 000 metric tonnes of magnesium is produced annually [19]. The production viability of magnesium from serpentine waste products and its economy should also be evaluated in the Nordic countries. But still today, there is no environmental impact assessment study on the carbonation method for CO$_2$ emission reduction, which is required to understand any environmental impact from the product of this carbon sequestration method before any waste handling plan is set up.

Figure 6 Heat-up and cool down of powdered serpentine and powdered Mg(OH)$_2$ samples in a N$_2$/CO$_2$ 85/15 %/%-vol gas atmosphere, showing the release of water during heat-up (50 K/min) and, after 10 min. at 1000 °C, uptake of carbon dioxide during cool-down (10 K/min). Pressure 15 bar for serpentine [12], 20 bar for Mg(OH)$_2$. 

![Figure 6](Image)
4.2 Extraction of Magnesium Oxides from Minerals, Integration with Other On-site Mining Activities

To be able to apply mineral carbonation in large scale the problem of transporting of the mineral or the carbon dioxide must be solved. In Finland most CO$_2$ sources are located far away from the mine where the mineral is coming from and the product returns to, preferably. To reduce costs and environmental effects the mineral should be transported as magnesium hydroxide. By extracting Mg(OH)$_2$ already at the mine the mass to be transported could be decreased by 37% for serpentine and 17% for olivine. Another benefit would be the integration of the extraction of magnesium hydroxide with other, already existing, mining activities. For example, at Hitura only part of the mined ore produces nickel and copper economically, and huge amounts of ore with a too low metal concentration have to be stored as waste. Most of these are various magnesium silicates, so-called serpentinite. A co-production of magnesium oxides and other mining products could make both processes profitable.

Also, the extraction of magnesium oxides from the minerals is energy intensive: as mentioned the decomposition of the mineral into magnesium oxide, water and quartz requires temperatures above 900ºC for serpentine. Although the carbonation process itself is exothermic the extraction of magnesiium oxides (decomposition of the mineral) requires energy input. (The wet process, using hydrochloric acid, with MgCl$_2$ as reaction intermediate, studied earlier at different institutes in the USA [2,4,7] is even more energy intensive). This energy input could be covered by waste heat from other industrial processes, such as metal production. At the same time the magnesium oxide could be used to capture the CO$_2$ emissions produced by those processes. This concentration of different processes near each other could reduce the transportation by almost 100%. At the same time the processes could be integrated into each other to maximize the efficiency of energy use.

5 CONCLUSIONS / FUTURE WORK

From the Finnish point of view mineral sequestration seems to be the most suitable if not the only possibility to reduce the CO$_2$ emissions, especially if Finland doesn't shift its energy policy towards nuclear power. A reduction of about 5% CO$_2$ emissions would be enough to decrease CO$_2$ to the level agreed upon in Kyoto in 1997. In Finland the required mineral seems to be available in sufficient amounts for such a reduction to be obtained by mineral carbonation. The Hitura serpentinite deposit mentioned above could fixate all the CO$_2$ from a 500 Mw$_{coal}$ coal-fired power plant for approximately 15 years (assuming complete conversion of MgO to MgCO$_3$).

At a mineral carbonation efficiency of 100% for each ton of CO$_2$, 2.18 tons of mineral serpentine would be required. To capture the CO$_2$ released by the Salmisaari power plant at least 2 Mt serpentine would be required per year. A 5% reduction in CO$_2$ emissions for all Finland would require a quantity of 6.11 Mt serpentine per year. Every ton of carbon dioxide would result in 0.66 tons of quartz and 1.92 tons of magnesium carbonate: 1 ton of serpentine produces 1.2 tons of solid reaction products. These should, preferably, be returned to the mine, if not the CO$_2$ itself is transported to the mineral deposit by pipeline.

The material is already produced as a side product at several mines, but increased mining would be required. The mining of magnesium silicates could also improve the efficiency of the metal
production. Some sort of integration of metal ore processing and magnesium silicate treatment to
give magnesium oxide, MgO would be highly beneficial, also from a process economy point of
view. At this point magnesium silicate is still a side product of metal mining but as soon as a valuable
use for the mineral is discovered, its price will certainly increase. This will be reflected directly by the
costs of electricity and heating.

In the experiments of this study the direct carbonization of a rather pure mineral serpentine and a
rather pure magnesium hydroxide have been tested. Isothermal tests with serpentine at 200°C
(392°F) give no change in the mineral’s carbonate content, whilst heating to 1000°C (1832°F)
followed by cooling to 200°C shows a low level of carbonation after a relatively long time. Tests
with a magnesium hydroxide sample showed a catalytic effect of H₂O, whilst no significant effect of
O₂ is found, when added to a CO₂/N₂ mixture.

A kinetics analysis showed, for this sample at a total pressure of 1 bar, a maximum conversion rate
at a temperature around 350°C (662°F), above which thermodynamics become unfavourable, and
below which the carbonation rate decreases. It is concluded that mineral carbonation should be
carried out at this temperature optimum, which is slightly affected by the flue gas composition.

The effect of pressure (15 or 20 bar, with 15 vol-% CO₂ in the gas) could not yet be quantified since
the release of H₂O from the serpentine and Mg(OH)₂ samples during heat-up is accompanied by
other effects that change the mass of the sample.

If direct carbonation is possible with Finnish magnesium silicate minerals it will certainly need a
catalyst to reach reasonable conversions within a realistic timeframe. The first results with small
amounts of NaCl, NaHCO₃ and Al₂O₃ added to Mg(OH)₂ did not show an improvement, however.

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