The possibilities of olivine enhanced weathering in paved road construction

A Literature Review

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Writing assignment
Utrecht University
Supervisor from Utrecht university Jaco Appelman
Second reviewer Jasper Griffioen

Abstract

This article reviews the possibility of using enhanced olivine in road construction in the Netherlands. Olivine is a mineral that is easily accessible. It is found all over the earth's mantle. It can take up about 1 kg of CO_2 per 1 kg of olivine. However, this process goes very slow. Therefore, enhancing weathering is an interesting solution to our CO_2 problem. With optimal conditions in the Netherlands, it is expected that olivine takes about 30 years to be completely weathered. Olivine needs to react with water and CO_2 to form bicarbonate that capture CO_2 in a solid form. Olivine is still not widely accepted because of environmental uncertainties. Two possible application of olivine enhanced weathering have been found. Olivine can be used mixed as aggregate in the top layer of a road, in the asphalt. Cars drive on the road, wearing the olivine into smaller particles, enhancing the weathering. Olivine can also be scattered in the roadside. The olivine rock needs to have a grain size of 10 µm to sequester 100% of the potential CO_2 within 30 years. Olivine does not only take up CO_2, but it also increases the pH and alkalinity of soil and water. This is a positive side effect, as Dutch soils are increasingly getting more acidic. Increasing the alkalinity of the water helps prevent global ocean acidification. A possible negative side effect is the release of nickel. A high concentration of nickel is toxic for many plants. It is still unknown how this plant toxicity mechanism works. Future field research should be done to investigate if olivine releases to much nickel and is harmful for local ecology. If this is the case, mother nature offers solutions to counter this negative side effect. Nickel hyperaccumulator plants are able to filter the soil from nickel and collect it in their biomass. This filtering of nickel into biomass also creates a way of harvesting nickel in an environmentally friendly way. Lugworms grind soil inside their body and filter any heavy metal. Their enzymes bind the heavy metals and store them in the cells. The heavy metals are no use for the lugworms, however, the soil they excrete is free from nickel. On top of that, they also grind the soil particles increasing the relative surface area. It can be concluded that olivine enhanced weathering applied in asphalt and roadsides can be a environmentally friendly way of capturing CO_2. There is still some uncertainty about the effects of high concentrations of nickel, however, there are bio-inspired solutions possible to filter the nickel before it harms the environment.

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Introduction

The earth is 4,5 billion years old. It is estimated that volcano's produce three hundred million-ton CO_2 per year. The total CO_2 that has been emitted during the lifetime of our planet is therefore extremely high. If there would not be any process that regulates the CO_2-balance in the atmosphere, the atmospheric pressure would be a hundred times denser then it is at this moment. The temperature would be around five hundred degrees Celsius due to the greenhouse effect caused by the high concentration of CO_2 in the atmosphere. No life that we know would survive in those extreme circumstances. However, there is life and the atmospheric pressure and temperature are not that high. Therefore, there must be a process that regulates the CO_2-balance in the atmosphere. This natural process is called rock weathering or mineral carbonation. Mineral carbonation is the reaction of minerals with water and CO_2, whereby the CO_2 is first converted to bicarbonate in solution. Then, the bicarbonate solution is transported to the sea through rivers. In the sea, the bicarbonate solution is used as a building block. Corals, shellfish and plankton convert the bicarbonate solution into limestone, which is the sustainable natural storage facility of CO_2. This process has captured roughly a million times more CO_2 than the oceans, atmosphere and biosphere together. (Schuiling, 2017)

However, this natural process of capturing CO_2 is very slow, it takes thousands of years to convert CO_2 from the atmosphere into limestone. Compared to the age of the earth, humans are only recently living on this planet. Since the industrial revolution, human CO_2-emissions have exponentially increased. Burning fossil fuels have been the main source of our emissions. Circa 85% of our global energy production is done by burning fossil fuels. Due to the increased CO_2-emissions caused by humans on top of natural CO_2-emissions, the CO_2-concentration in the atmosphere has increased from 270 parts per million (ppm) to 415 ppm within three hundred years. The natural process of capturing CO_2 is too slow to keep up with our increasing CO_2-emissions. Since a couple of years, the green revolution has started. global goals have been set, aiming for a decrease in CO_2-emissions. The goals aim to decrease energy usage and increasing sustainable energy production, such as wind, water and solar energy. However, it is estimated that the worlds energy requirement will only increase for the next decades, untill at least 2030 (IEA, 2004). On top of that, only reducing CO_2-emissions will not be enough. If climate change is to be reversed, the CO_2-concentration in the atmosphere needs to be lowered back between 250 and 350 ppm within a short period of time. The natural process of capturing the CO_2 from the atmosphere takes too long, as the present CO_2-concentration is already high enough to induce a positive feedback loop on climate change. Therefore, besides reducing CO_2-emissions, the atmospheric CO_2-concentration needs to be actively reduced by capturing.

Capturing CO_2 from the atmosphere and storing it is called Carbon Capture and Storage (CCS). Examples of CCS are planting trees, ocean fertilization and storing CO_2 in former gas- and oilfields. These methods are very expensive and take a lot of time and energy to develop and implement. As mentioned earlier, mineral carbonation is by far the most effective natural way of keeping the CO_2-concentration in balance. Instead of finding solutions that require a lot of technological developments, like filtering the air and converting the captured CO_2 into biofuels (Wurzbacher, 2017), we should look at nature and be inspired by its process mineral carbonation. Using olivine, we can achieve a relatively fast and cheap way of mineral carbonation. Olivine is the most abundant mineral on earth and is relatively effective in capturing CO_2. This innovation of optimizing nature's carbonation process is called enhanced weathering.

We need to lower the atmospheric CO_2-concentration. This can be done by introducing fine olivine where possible. Large projects where sand is normally used form a possibility where large quantities of olivine can be introduced, by replacing sand with fine olivine. Road constructions are often projects that use large quantities of sand. Therefore, it is interesting to investigate what the possibilities are for using olivine instead of sand in road construction projects. In this review road construction means the construction of paved roads only.

This review will investigate the research that has been done on olivine. It will elaborate on the benefits and the downsides, like the heavy metals that are released during the reaction with CO_2 and olivine. There will be a focus on how this mineral can be used in our society, especially in road construction, and how the corresponding problems might be solved by looking at innovations inspired by nature.

Research question: How can inspiration from nature promote the use of olivine in the construction of paved roads?

The following sub-questions are addressed:

- What is olivine and how does it react with CO_2?
- What are the applications of olivine, focusing on the Netherlands?
- How can olivine be used in road construction?
- What are the side effects of using olivine to capture CO_2?
- How does the reaction of olivine with CO_2 affect the soil?
- How can nature inspire us to enhance the weathering of olivine?
- How can nature inspire us to solve the negative side effects of olivine, focusing on the use of olivine in road construction?

What is Olivine?

Olivine is a mineral that is formed deep down in the earth into magma. This magma is rich in magnesium. Olivine reaches the surface of the earth when the plateaus shift or during a Vulcanic eruption. Olivine is the most abundant mineral on earth, it can be found everywhere. The chemical formula for olivine is shown below:

$$Mg_2SiO_4 \quad (1)$$

In reality, the average composition consists of 92% magnesium and 8% iron. The proportion of magnesium and iron depends on the location where it is found. It is important for enhanced weathering that the proportion of Fe is as low as possible, as Fe_2SiO_4 has a net zero CO^2 sequestration rate (Veld et al., 2008; Wogelius and Walther, 1991). The structure of olivine has the property that is the fastest weathering mineral. CO_2 is captured during the weathering process and converted into bicarbonate (Schuiling, 2001; Schuiling, 2017; Soubrand-Colin *et al.,* 2005). The reaction of olivine with CO_2 in showed below:

$$Mg_2SiO_{4\,(s)} + 4CO_{2\,(g)} + 4H_2O_{\,(l)} \rightarrow 2Mg^{2+}_{\,(aq)} + 4HCO_3^-{}_{(aq)} + H_4SiO_{4\,(aq)} \quad (2)$$

This reaction shows that per kilogram pure olivine (with a 100% magnesium) 1,25 kg CO_2 is captured. The CO_2 is converted and stored into bicarbonate. In a non-buffered system, this reaction causes a slight increase in pH. It is important to note that a part of the captured CO_2 can be released again when the bicarbonate solution precipitates with magnesium as magnesite ($MgCO_3$) (Bakker *et al.,* 2010) This reaction is showed below:

$$2Mg^{2+}_{\,(aq)} + 4HCO_3^-{}_{(aq)} \rightarrow 2MgCO_{3\,(s)} + 2H_2O_{\,(aq)} + 2CO_{2\,(g)} \quad (3)$$

If this happens, the net kg CO_2 that is captured per kg olivine is 0,6. However, this reaction does not occur under ambient conditions in the Netherlands (Hostetler, 1964). Magnesite is only formed in elevated temperatures (a minimal of 40 degrees Celsius) and high pressure. The limiting factor of the CO_2 sequestration reaction (2) is the dissolution rate of the reacting silicate mineral. Rather than the precipitation of magnesium as magnesite (formula 3) (Hangx and Spiers, 2009). Dissolution of olivine is dependent on the adsorption of H^+ and exchanging its Mg^{2+} ions.

Weathering of olivine only happens at the surface where the mineral is exposed to CO_2 and water. The larger the surface the faster the weathering. Grinding olivine will decrease the particle size and increase its surface area and therefore increase the weathering speed. However, the amount of CO_2 per kg olivine that is captured remains the same.

Olivine is one of the minerals that are responsible for keeping the CO_2-concentration in the atmosphere in balance. Natural weathering of minerals is the process that nature has been using far before humans existed. Without this process, life as we know it would not exist. As shown in formula 2, one of the end products is a bicarbonate solution. Eventually, this bicarbonate solution reaches the sea and is used as a building material by coral, shellfish and plankton. It is then converted into solid carbonate rock. These carbonate rocks offer the largest and most sustainable storage capacity for CO_2. Large quantities of olivine are easily accessible for mining and it can be mined with low costs and low incidental CO_2-emissions (Schuiling, 2017). Olivine can be found anywhere on the planet. It is the most common mineral on earth. That is why accelerated weathering of olivine is a very interesting sustainable solution for our CO_2 problem.

Olivine weathering

Factors that influence the weathering of olivine

Experiments in lab conditions show relatively slow weathering speeds, However, in the real world the weathering speed is much higher, due to biotic factors like microorganisms, lichen, ants, vascular plants and lugworms (Schuiling, 2017). It is estimated that in a temperate climate a couple of ton pulverized olivine is capable of actively capturing CO_2 for thirty years (Hawken, 2017). Many factors have an impact on the weathering rate of olivine. It is not easy to answer in what degree the organisms and the abiotic factors affect the weathering process of olivine because a lot of factors influence the weathering process and they are often very complex (Brady *et al.*, 1999). The factors are often coupled with one another, which makes it hard to investigate one factor in isolation.

Biotic factors

The weathering of olivine is enhanced through some combination of organic acid secretion by lichen, microorganisms, ants and possibly other organisms (Hiebert and Bennett, 1992). Microbial respiration of organic matter is able to drastically increase the soil CO_2-concentration, which directly affects the dissolution of silicate minerals like olivine (Perez-Fodich and Derry, 2019). Physical exposure to fungal hyphae and vascular plants is another process that enhances the weathering of olivine (Berthelin, 1988). Plants, for example, contribute to erosion through their roots penetrating cracks in rocks and providing a porosity preferential for reactive gases and fluid flow. On top of that, they also regulate water runoff and sustain soil water through evapotranspiration (Perez-Fodich and Derry, 2019). Bioturbation is another process that increases the weathering rate of minerals (Schwartzman, 2002).

Lugworm

Lugworm, also called sandworms, are an interesting biotic factor to mention separately from the other biotic factors. Lugworms can enhance the weathering of olivine by milling the mineral and increasing the total surface area. Furthermore, they have the ability to prevent heavy metals from leaching into the soil during the reaction of olivine with CO_2. This phenomenon and its possibilities will be elaborated on in the chapter “Bio inspired innovations”.

Abiotic factors
Other factors that play a role in the rate of olivine weathering, and thus the rate in which CO_2 is captured, are the following abiotic factors:

- Water;
- Formation of iron oxide layer;
- Grainsize;
- Temperature;
- Movement;
- pH;
- Saturation.

Water
Olivine is able to capture CO_2 only when in contact with water (formula 2). Water needs to be able to run off, otherwise, saturation occurs (see saturation).

Formation of iron oxide layer
Olivine consists mostly of magnesium (formula 1). However, a small portion of olivine consists of iron (Fe), about 5%. This small portion of iron precipitates during the reaction of olivine with water and CO_2 (formula 2). This precipitation of Fe forms an iron oxide layer on the remaining olivine. The layer of iron oxide prevents olivine from further weathering. It forms a layer between the olivine and external CO_2 and water.

Grain size
The smaller the grainsize of the olivine, the larger the relative surface area. This enhances the weathering of olivine. (Figure 1)

Temperature
The warmer the temperature the faster the reaction (formula 2) occurs.

Movement
Movement is necessary to grind off the iron oxide layer. This will allow olivine to continue weathering. Movement also grinds the olivine particles. This leads to a larger surface area and enhances the weathering process.

pH
Olivine weathering causes its environment to become more alkaline. Therefore, the more acidic the environment the faster the olivine weathers. This means that olivine weathering causes its reaction to slow down as it creates a more and more alkaline environment.

Saturation
One of the abiotic factors that influence the weathering rate of olivine is the saturation of end products mentioned in formula (2). When olivine reacts with water and CO_2, 3 products are formed. Magnesium, bicarbonate and silicic acid. The limiting factor of the CO_2 sequestration reaction (2) is the dissolution rate of the reacting silicate mineral, as the solution can become saturated. However, Schuiling and Wilson (2011) found that the concentration of silicic acid never reaches a state of saturation in natural weathering conditions. Because enhanced weathering is much faster than natural weathering, it is important that the water is running, so that no saturation can occur.

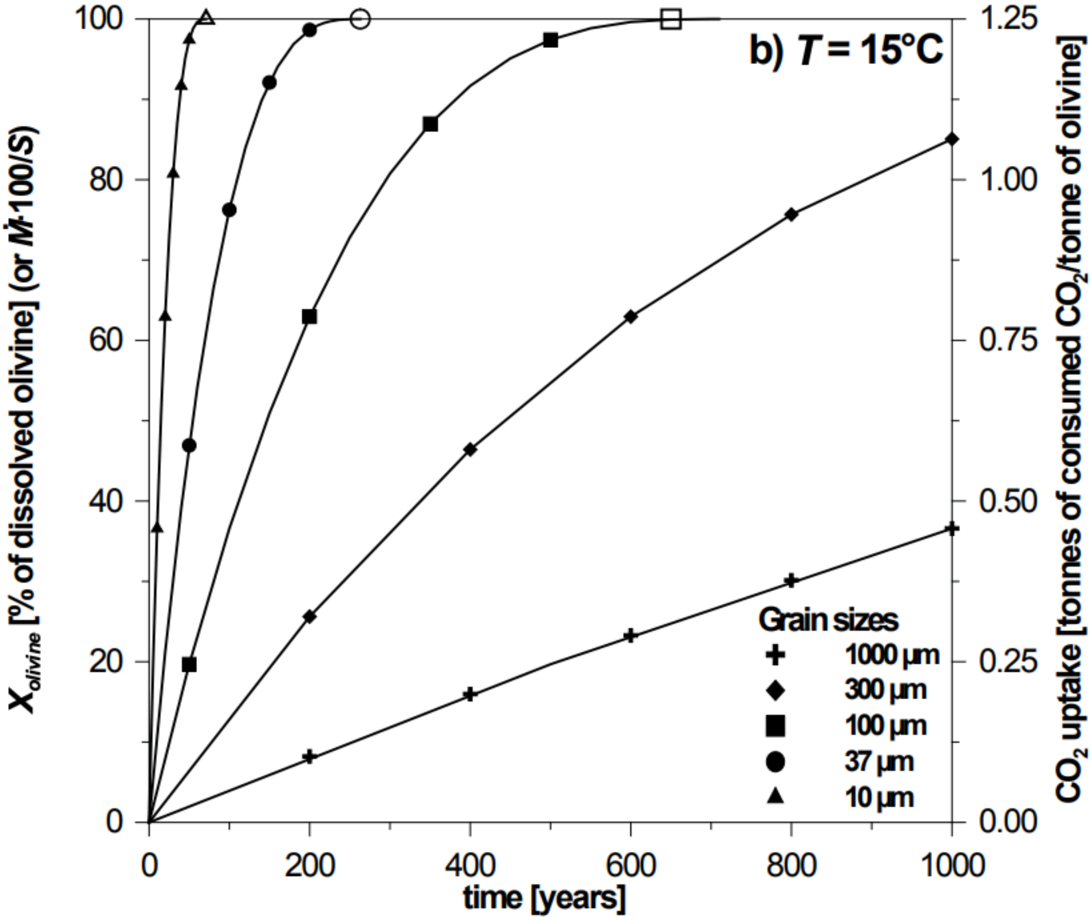

Figure 1. Olivine's reaction as a function of time with an average temperature of 15 degrees Celsius (Hangx & Spiers, 2009).

Figure 1 shows an estimation for the weathering speed of olivine at different grain sizes. It shows that olivine with a grain size of 10 µm takes 23 years to be 100% weathered. However, this data is valid for an average temperature of 15 degrees Celsius. The average temperature in the Netherlands over the last ten years has been around 11 degrees Celsius. This implies a small decrease in weathering speed when olivine is used in the Netherlands. It is estimated that with a 10 µm grain size, olivine takes about 30 years to completely weather (Hawken, 2017).

Factors that influence the CO2 capturing efficiency

1-Kilogram olivine is able to capture 1,25 kg CO_2. However, before olivine is deployed to capture CO_2, several processes have proceeded. To get a complete overview of what the actual impact of olivine is on the CO_2 concentration in the atmosphere, the lifecycle of this process should be investigated. Table x, x and x show an overview of the CO_2 efficiency of olivine per lifecycle phase.

Table x. CO_2 efficiency loss for olivine CO_2 sequestration due to extraction (Bakker *et al.* 2010; Hangx and Spiers 2009).

Mining raw olivine in Norway	CO_2 efficiency loss (%)
	0.33

Table x. CO_2 efficiency loss for olivine CO_2 sequestration due to grinding (Hangx and Spiers 2009).

Grain size (μm)	CO_2 efficiency loss (%)
1000	0.31
300	0.52
100	0.85
37	1.51
10	11.00

Table x. CO_2 efficiency loss for olivine CO_2 sequestration due to transportation from Norway to Rotterdam (Hangx and Spiers 2009).

	Efficiency loss per 100 km	Distance (km)	Total efficiency loss (%)
Barges and coastal ships	0.24	1000	2.4
Freight trains	0.16	0	0
Trucks	1.11	100	1.1
Sum			3.5

When olivine is extracted from the nearest sources in Norway, Greenland or Turkey and ground into the most optimal grain size of 10 μm, the efficiency reduction of olivine sequestration would be around 10-20%. Since most olivine-rich rocks are about 60% olivine, more realistic efficiency loss is about 15-30% (Hangx and Spiers, 2009). This translates in a CO_2 sequestration capability between 0.88- and 1.06-ton CO_2 per ton olivine.

Side effects

Olivine that has been ground and sand have similar properties, while olivine can also capture CO_2, which is an interesting bonus effect. Olivine, however, has some other side effects that need to be investigated before it can be used as a sand replacement in road construction.

Increase in pH

Soil pH increases when olivine weathers (Amann *et al.,* 2020). pH increases as CO_2 dilute in water, binds to the mineral olivine and forms bicarbonate, Mg^{2+} and silicic acid.

Ten Berge *at al.* (2012) show that the pH of the soil and the water increase when olivine weathers. 9.5 kg of soil was mixed with 1.0 kg of olivine (Ten Berge, 2012). This was the maximum concentration of olivine relative to the soil. With this amount of olivine, within 32 weeks the pH increased from 4.89 to 5.96, an increase of 1.07.
Groundwater pH was measured after 32 weeks. No significant difference was measured with small amounts of olivine added to the soil. Only the highest two concentrations of olivine showed a significant increase in pH. When 200 grams was mixed with 11 kg of soil an increase in pH of 0.44 was measured. When 1 kg of olivine was mixed with 9.5 kg of soil an increase in pH of 1.20 was measured compared to the control (Ten Berge, 2012).
The absence of pH response with lower olivine doses is not fully understood. However, they might reflect the buffering process by the soil system.

The benefit of olivine weathering is that it combats soil acidification. This can be useful for agriculture as they suffer from acidic soils due to nutrient depletion and fertilizing.

Change in alkalinity

Alkalinity is the capacity of an aqueous solution to neutralize a decrease in pH. It displays the buffer capacity of water. In Dutch water, the alkalinity is dependent on the concentration of diluted bicarbonate. A high concentration of bicarbonate (HCO_3^-) is toxic to water fleas (Hoke, 1992). At what concentration is still unknown. On the other hand, increased alkalinity is favourable for snails and shellfish, as HCO_3^- is a building block for their shells.

The change in alkalinity in soil water is shown by Ten Berge (2012). After 32 weeks a difference was measured only when higher doses of olivine were mixed with soil. When 200 grams of olivine was mixed with 11 kg of soil an increase of 1.40 mmol/l in alkalinity was measured. When 1.0 kg of olivine was mixed with 9.5 kg of soil an increase of 2.36 mmol/l in alkalinity was measured compared to the control.

Silicic acid

Silicic acid (H_4SiO_4) is one of the products that is formed after olivine reacts with CO_2 and water (formula 2). Silica has a very little biological function. The silica cycle is controlled by diatoms. Once the silicic acid has reached the ocean, diatoms take up the silica and use it to form their cell walls (Amo and Brzezinski, 1999).

Bicarbonate

Bicarbonate (HCO_3^-) is one of the products that is formed after olivine reacts with CO_2 and water (formula 2). The bicarbonate eventually reaches the oceans. Bicarbonates precipitate with metals like calcium by marine organisms and end up at the bottom of the ocean in the form of limestone. As discussed before, a high concentration of bicarbonate is toxic for water fleas. However, this mechanism is still unknown and should be investigated with future research.

Release of heavy metals

During the weathering of olivine, ions such as Fe2+ and Mn2+ leach into the environment. These two particular metals rapidly oxidize and precipitate and form an increasingly thick, red layer at the top of the weathering surface (Spivak-Birndorf *et al.,* 2018). Other metals like magnesium and silicon are highly soluble and distribute together with meteoric waters. Ni, on the other hand, binds to Fe oxyhydroxide particles and thus remains in the uppermost oxide-rich zones of the weathered profile (Fan & Gerson, 2011; Dublet *et al.,* 2012; Butt & Cluzel, 2013). As described above, Fe^{2+} precipitates and forms rust. This can be important to take into account when olivine is used in asphalt.

Ni release is one of the negative side effects of CO_2-sequestration through enhanced weathering. Not much research has been done on this topic, however, the concern of increased Ni flux is already there (Montserrat *et al.,* 2017). Monterrat *et al.* (2017) found much higher Ni trace concentrations in seawater compared to their control treatments with artificial seawater.

Many acknowledge the potentially harmful side effects of olivine enhanced weathering, through the leaching of harmful trace elements. Especially high concentrations of chromium and Ni are observed in soil solutions, where Ni concentrations even exceed the limits of drinking water quality (Amann *et al.,* 2020). Therefore, Amann *et al.* do not recommend the use of olivine in enhanced weathering.

The effect of high Ni concentrations in the soil is a significant reduction in enzyme activity, which directly negatively affects plant growth (Boros-Laiszner, 2018). The following questions arise: When is the Ni concentration in the soil to high? How much does olivine affect the Ni concentration in the soil? So far, Ni has been described as a harmful metal that leaches from olivine weathering. However, Ni is only harmful to the environment when the concentration is too high. No Ni in the soil would be bad for the environment as well, as Ni is essential for many bacteria and plants, as they require small quantities for their development, particularly due to its role in nitrogen metabolism (de Macedo *et al.,* 2016). Alibakhshi and Khoshgoftarmanesh (2015) reported that the nitrate concentration in plants can be reduced by small amounts of Ni, as Ni increases the activity of nitrate reductase. In nature, the availability of Ni varies dependent on the pH. Ni has a narrow dynamic range between toxicity and minimal requirement. Therefore, it is challenging to keep the soil's Ni concentration in balance. Adding small amounts of olivine might already disrupt this balance. Examples of Ni toxicity for plants are: Low nutrient uptake (Charles and Issac, 2014; Fabiano *et al.,* 2015), nutrient imbalances (Saad *et al.,* 2016) and decreased stomatal conductance (Velikova *et al.,* 2011). Ni can cause phytotoxicity by affecting the photosystems, through inhibiting electron transport chains and disturbing the Calvin cycle (Yusuf *et al.,* 2011).

How much is already in the soil?

In normal conditions, nickel in the soil and surface waters is less than 100 and 0.005 ppm, respectively (McGrath, 1995). However, nickel is becoming a serious concern during the last decades. More and more soils and waters become polluted, where the concentration of nickel reach up to 26.000 ppm (Alloway 1995; McGrath 1995) and 0.2 ppm in polluted surface waters (Zwolsman and Van Bokhoven 2007).

How much is too much?

The critical toxicity level of Ni in the plant is more than 10 ppm in sensitive species (Kozlow 2005), 50 ppm in moderately tolerant species (Bollard 1983; Asher 1991) and 1,000 ppm in Ni hyperaccumulator plants such as Alyssum and Thalspi species (Kupper et al. 2001; Pollard et al. 2002). The amount of nickel that plants take up is dependent on the amount of nickel in the soil, but also the pH, the concentration of other metals and organic matter composition (Yusuf, 2010).

How much does olivine release?

Spivak-Brindorf *et al.* (2018) show that during the enhanced weathering of Twin Sister's olivine in dilute HCl produced solutions, release a concentration of Ni ranged from 1.5 to 10.2 ppm. This is done in lab conditions, however, does give a rough estimation of the amount of Ni that is released. 1.5 to 10.2 ppm Ni released in the soil would only be a problem for sensitive species, or when the soil already contains a high concentration of Ni.

Applications of olivine

Olivine has a lot of application possibilities. Below is a list of several categories in which olivine can be used as a building material.

- Agriculture;
- Forestation;
- Railways;
- Buildings;
- Playing fields;
- Coastal defence;
- Suppression of poisonous dinoflagellates;
- Culturing diatoms for biodiesel production;
- Mining industry;
- Capturing CO_2 from natural emission sources;
- Road construction.

Agriculture
Olivine is capable of restoring acidic soils. Olivine leaches magnesium during its weathering. Magnesium is an essential mineral for the development of leaf green, chlorophyll.

Forestation
Similar to the application in agriculture, olivine is capable to restore acidic soils. As many forest soils are suffering from acidification.

Railways
CO_2-sequestration through olivine that is scattered over the inspection paths near railways. The first tests were executed by the Dutch Railways. The results were positive.

Buildings
Olivine can act as a CO_2-buffer in buildings. As schools and offices reach high CO_2-concentrations as the day ends. CO_2-concentrations of over 1000 ppm are reached at the end of the day. Rooftops have a huge unused surface area. These can be covered by olivine. Sandblasting can be done with olivine as material. Olivine does not create dangerous fine dust, therefore, is safe to use with sandblasting.

Playing fields
Gravel on tennis fields can be replaced by olivine. Olivine can also be scattered at Golf courses and playing fields that use artificial grass with sand.

Coastal defence
The surf at the beach causes the motion that enhances the weathering of rocks. Large builders of olivine can be deployed to defend our self from the sea.

Suppression of poisonous dinoflagellates
Dinoflagellates excrete a very poisonous solution when they die. Many fish die as a result. Dinoflagellates die when there is a shortage in silicates. Olivine can deliver the desired silicates and help the dinoflagellates survive when the concentration of silicates is low.

Culturing diatoms for biodiesel production

Diatoms can be used to produce biofuels. Diatoms consist of 50% fatty acids. Diatoms grow in the water on rocks, like olivine.

Mining industry
A lot of olivine needs to be mined for all these applications. This will take its toll on the environment, however, does not compare to the positive effect olivine has globally. At the end of the lifetime of a mine, they often turn into lakes. The olivine rocks that are still exposed will be in contact with water and continue to absorb CO_2 out of the atmosphere.

Capturing CO_2 from natural emission sources
Natural CO_2 emission sources are an easy target for olivine. For example, near the coast of Greece 2.2 million ton of CO_2 bubbles are rising from the bottom of the sea. Adding a hill made out of olivine at this location can easily take up lots of CO_2 as the conditions are very optimal for olivine weathering. The temperature is high, water is constantly in contact with the rocks and the water is moving due to the bubbles.

Using olivine in road construction

As shown above, olivine has several application possibilities. This review will focus on the applications of olivine in road construction. What are the possibilities of olivine in road construction?

Road construction is a process that is responsible for a lot of CO_2-emission. It is interesting to find innovations that can reduce the total CO_2 amount that is emitted during the construction of a road. Using olive to replace the sand that is normally used, is a promising innovation that can help reduce the CO_2-emission. Olivine has the potential of capturing a certain amount of CO_2 during the lifetime of the road.

Olivine is a silicate mineral. Olivine has the potential of replacing sand and silicates in constructing a road. Coarse olivine can also replace gravel and other coarse materials. However, olivine is more effective in capturing CO_2 the smaller the grain size (Figure 1).

Sand is classified by the Massachusetts Institute of Technology (MIT Textural Classification) with a grain size between 2000 and 60 µm. Gravel has a grain size of 2000 µm and bigger. As Figure 1 shows, replacing gravel with olivine would not be effective for CO_2 capturing, if no movement takes place that grinds the olivine into smaller particles. Even the smallest grain size of sand would be a size that is ineffective in capturing CO_2 within a short period of time. The optimal size of olivine would be 10 µm. This falls under the category of silt.

Gravel, sand and silicates are used during the construction of a road (Figure 2):

- Sand at the side of the road;
- Gravel sized aggregates in the wearing coarse;
- Making concrete;
- Constructing a base foundation.

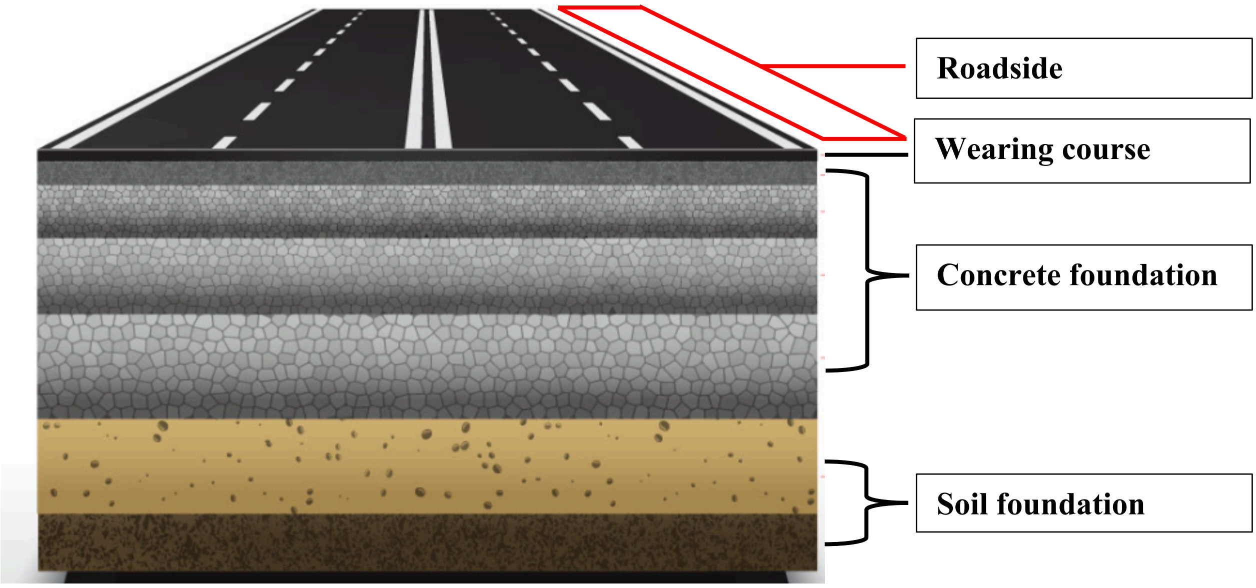

Figure 2. An overview of the layers of a paved road. The four layers that are categorized have the possibility of having olivine implemented.

Roadside (Figure 2)
Next to the paved part of the road, there is often a strip of unpaved road, the roadside. This consist mostly out of soil or sand. The roadside will slowly be overgrown with vegetation such as grass. Is olivine suitable soil material for vegetation growth? As discussed earlier, olivine weathering releases approximately 1.5 to 10.2 ppm into the soil. This would only negatively affect sensitive species. Or when the nickel concentration is already reaching the limits of the vegetation that is growing on site.

A factor that enhances the CO_2-uptake of olivine mixed in the soil, are the living organisms. These creatures increase the weathering of soil particles and thus the olivine particles. They do this by creating an acidic environment and grinding ingested soil particles as worms do. Soil also retains rainwater, causing olivine to be subjected to the chemical reactions with water for a longer period of time. While maintaining the inflow of new water from above and the outflow of old water to below.

Wearing course (Figure 2)
The wearing course is the upper layer of a road. The part that wears during its use. The wearing course is made from either asphalt or concrete. Asphalt is made out of aggregate and a bituminous binder. Concrete is also made out of aggregate. Aggregate generally consists of coarse gravel or crushed rocks such as granite, or limestone. This can be replaced by coarse olivine particles because cars enhance the weathering through wearing the materials. Fine aggregate is generally made form finer materials such as sand. This fine aggregate made out of sand can also be made from olivine. Is this case both aggregate types are interesting, as the top layer weathers much faster because cars drive on the material wearing it into smaller particles. The aggregates used in making the wearing course asphalt and concrete can be made from olivine.

Concrete foundation (Figure 2)
Concrete is also used as a foundation to support the top layer. Concrete layers that form the foundation of the top layer can be made out of fine aggregate, which can be made out of

olivine. Coarse aggregate is not an option to be replaced by coarse olivine. As the foundation does not undergo wear from cars driving on top.

The other material that makes concrete, cement, consists of 72% silicates. Because olivine is a silicate mineral, cement can be made from olivine. The usual grain size of cement is between 7 and 200 μm (Building Materials in Civil Engineering, 2011). Small grained cement consisting out of olivine would, therefore, be a realistic option for implementing olivine in reconstructions. However, this layer does also not undergo wear of cars driving on top. This excludes this option as well.

Soil foundation (Figure 2)
Soil forms a thin layer around the earth's surface created through the weathering of rocks. Soil consists out of minerals particles, organic materials, water, air and living organisms. For the stability of the road, suitable foundation soil is necessary. The soil that is used to construct the roads on must meet certain standards. It is interesting to investigate whether olivine would be fitting for the mineral type that forms the base of the soil foundation in road construction. What size of grain would be optimal for foundation properties? At the same time, grain size as small as possible for optimal CO_2-capturing.

Olivine only reacts with CO_2 when it is in contact with water. Water needs to pass through the asphalt's top layer to reach the layer beneath. Most asphalt types are porous where water is able to run through (Poulikakos & Partl, 2009). However, the concrete foundation does not let enough water through for the soil foundation to be an op system of water. Therefore, the enhanced weathering of olivine would not be applicable as a soil foundation.

Road drainage system

It is important to address the road drainage system, as the olivine weathering products are not directly released into the environment. The weathering products are in solution with water and will drain to the side of the road into the drainage system. The water will flow to the side of the road due to the slight bulging of the road. There the water will leach into the roadside ditch and groundwater.

There are two different ways the water is drained away from the road. One is via draining into the roadside and naturally dropping down to the groundwater through the soil. The other system is draining the water via gutters. These gutters guide the water away into the roadside ditches.

Adding a filter in the road drainage system will prevent heavy metals from leaching in the surrounding soil. When metals like nickel accumulate, they can be extracted using some kind of filter. This filter prevents harmful metals to reach the environment, as the filtered water will drain into the surrounding soil next to the road.

This adjustment of adding a filter is easily applicable when a gutter system is used to drain the water. However, when the water is naturally drained through the soil in the roadside, adding a filter can be challenging.

A secondary option would be to add a filter underneath the wearing course. This only applies if the water is able to run through the asphalt layer. ZOAB (zeer open asfalt beton: very open concrete asphalt) is able to let the water slowly drain through to the layers below. Drainphalt is an innovation for a new type of asphalt that is able to soak up a lot of water and let it easily sip through to the layer below. When the water has passed the top layer, it can be run through a layer that filters the water before it leaches into the groundwater. The filter would be an additional layer of road foundation underneath the wearing course.

A filter does not only prevent toxic metals from leaching in the surrounding soil, but there is also a big opportunity of gathering raw materials. Nickel and manganese are both metal that is used to produce batteries. Electric vehicles are in rising popularity. This makes the two metals in high demand. Adding a filter and filtering these metals is a way of gathering these metals in an eco-friendly manner, as it does not involve mining. This makes the mining for olivine less bad, as it partially eliminates mining for nickel and manganese.

When the filter is located in a gutter water drainage system it is easily accessible. After filtering the metal, they can be easily extracted and used for production processes. When the filter is incorporated in the foundation of the road, it is less accessible.

Bio inspired innovations

Lugworms

Lugworms grind the olivine into small grain-sized olivine sand. During this grinding, the lugworm absorbs several minerals that are included with the olivine. This means that the lugworm filters the olivine from its heavy metals and grinds it into small grains. This is a win-win situation, as olivine takes up CO_2 faster when it is small grain-sized and the heavy metals are not present anymore. The whole discussion about altering the environment when those heavy metals, nickel especially, are released into the soil by harming local plants and bacteria, is completely negated. Before using olivine in road construction as a sand replacement material, the olivine should be ground into small grains and been filtered from its heavy metals. This can be done by imitating the grinding process of lugworms.

Lugworms do not grind their food via teeth as we do. Lugworms have a muscular gizzard that grinds everything by contracting. The soil acts as grinding material as particles of soil and food are ingested together. The contraction of the gizzard muscles compresses those particles against each other, together with fluid. In the end, the ground food is absorbed, the heavy metals and other toxins are removed, and the ground soil particles are excreted.

The digestive system of a lugworm is capable of detaching heavy metal ions from the soil. This happens via various enzymes. After detaching the metal ions, the ions are locked up in the tissue of the worm, this prevents the ions from being released back into the environment.

A relevant bio-inspired innovation inspired by the grinding process of a lugworm. A process where the olivine is first ground into smaller particles to increase the speed of CO_2 uptake. During this grinding process, a liquid with a similar function as the enzymes of a lugworm is mixed with the olivine. The fluid detaches the nickel ions from the mineral. Nickel is the only potentially harmful metal that leaches into the environment during olivine weathering. This is explained earlier in this review. Then the fluid is separated from the olivine particles, which are then ready to be used for enhanced olivine weathering. This fluid contains a high concentration of nickel ions which can be used for other purposes. Nickel is a raw material mostly used in stainless steel construction.

Olivine is already being used. Before it is used it is ground into smaller particles. The only adjustment in this process is the addition of a fluid that extracts the nickel ions. The idea is that this fluid is running through olivine that is being ground. The running fluid creates a flow of nickel enriched fluid. This fluid can be recycled if the nickel ions are filtered out of the fluid. Nickel is another material that can be sold along with olivine. Only the nickel that is released during the grinding and the nickel that is exposed to the surface can be extracted during this process. However, olive will still release nickel during its weathering when it is applied in road construction. The lugworm continuously grinds the particles and absorbs the released heavy metal ions.

Adding another natural mineral zeolite to olivine can prevent heavy metals from leaching into the environment. Olivine enhanced weathering releases a concentration of 1.5 to 10.2 mg/L Ni (Spivak-Brindorf *et al.* 2018). Belova (2019) shows that by a concentration between 0.5 and 3.5 mg/L Ni zeolites are promising sorbents for extracting heavy metal ions from aqueous solutions. The reaction occurs in room temperature, in water without any added chemicals. Zeolite can act as the lugworm's enzyme, that continuously absorbs the heavy metals that are released during the weathering of olivine.

Ants and termites

Dorn (2014) found that the weathering of olivine went faster near termite- and anthills. Schwartzman (2002) found that increased bioturbation is one of the processes that cause increased weathering of minerals near termite and anthills. Further details of what processes caused by ants and termites that are responsible for the increased weathering of minerals are still unknown. Appling olivine at the roadside is therefore realistic, as the bioturbation from the micro-organisms enhances the weathering.

Acid

As described earlier, biotic factors have a positive effect on the weathering rate of olivine. Many of these biotic factors are a great example of how to increase the CO_2 capture rate in enhanced olivine used for road construction.

- Many plants and mycorrhizal fungi live in symbiosis with each other (Van Schöll *et al.,* 2008; Taylor *et al.,* 2009). Several organic acids are excreted in this symbiosis, by the fungi. The plants make use of these acids by taking up the mineral constituents. This is only possible because the acids dissolve the minerals. A symbiosis is always a win-win situation. In return, the plants provide sugars for the fungi.

- Lichens and rock-surface fungi are pioneer colonizers of rocks. They play a significant role in the weathering of rocks. They excrete acid that attacks the underlying rock (Williams and Rudolph, 1974; Morando *et al.,* 2017). With their small biomass and the fact that they dissolve the underlying rock, they create the first layer of soil for other organisms to settle on.

The matching factor in the two examples described above is acid. Acid enhances the weathering of olivine because minerals quickly dissolve in acid. On the other hand, olivine has the property of increasing the pH of the soil. While the olivine weathers best when the soil is as acidic as possible. The challenge is to create an environment that is as acidic as possible without negatively affecting the vegetation and keeping it acidic while olivine weathering increases the pH.

Ensuring a roadside that is rich in biodiversity will enhance the weathering of olivine at the roadside, as plants and micro-organisms form symbiosis and release acids that enhance the weathering of olivine.

Motion by water

A different process that increases the weathering rate of olivine is motion. Motion through running water. When olivine locates itself in rivers, shallow waters with strong bottom currents and the surf of beaches it is moved by the current of the water. Olivine is ground into smaller pieces by hitting other hard objects. Slivers of olive bounce off the rock and have a very fast weathering rate, as their surface area per mass is relatively high. This method of grinding is similar to the grinding of soil particles that happens in the gizzard of a worm, explained earlier. The result and the process are similar. However, the system is different. This time the running water powers the motion of the rocks. A very modest imitation of a surf is able to knock of slivers of olivine (Schuiling, 2011). Another reason why motion enhances olivine weathering is that rocks in a fixed position often develop a thin silica-rich layer. This layer prevents further weathering as CO_2 is not able to react with this silica-rich layer (Schuiling, 2017).

Ensuring an open system where enhanced olivine implemented, will prevent saturation, silica formation and will grind the olivine grains, increasing the surface area.

Using water instead of using machinery that runs on fossil fuels to grind the raw olivine into the desired small grains. Like nature creates its beaches by grinding rocks from the mountains into sand. The large rocks grind into smaller and smaller particles as they travel through rivers and end up at the ocean.

Nickel hyperaccumulator plants

There are about 400 species that are able to hyper accumulate nickel (Van der Ent *et al.,* 2013). These plants are resistant to very high nickel concentrations in the soil. They collect the nickel in their biomass. Tognacchini *et al.* (2020) show that phytomining using hyperaccumulator plants is a possible option to clean up contaminated soils. The nickel hyperaccumulator plants are able to take up the nickel and store it in their biomass. This way the nickel can be easily harvested. A natural way of filtering and farming nickel.

Discussion and conclusion

After reviewing existent literature and lessons from nature, using olivine enhanced weathering in asphalt and roadsides is realistic. Knops and Lenferink (2018) estimate based on their simulations that the release of Ni from olivine enhanced weathering in practical applications in the Netherlands has no negative effect on the ecosystem, therefore the possibilities for olivine application and CO_2 sequestration are endless. However, high nickel concentration is certainly toxic to plants. However, nickel toxicity mechanism of plants is still very unknown. Therefore, field research should be done, measuring the nickel contamination in the ecosystems when olivine is applied in asphalt and roadsides without any filter and its effect on nearby plants. It should show the amount of nickel that is released and is taken up by the plants. An olivine road has already been piloted in Groningen. It was constructed in 2017. Data of this pilot is still being produced and monitored. It is too early to draw any conclusions.
Solutions preventing nickel contamination can be inspired by nature. For example, filtering the nickel from olivine when grinding into smaller grains, as the lugworm does. Increasing biodiversity at roadsides, causing more bioturbation and acid release during symbiosis. Ensure an open system for the water to be able to run off, preventing saturation, high pH levels and high concentrations of metals.
Nickel hyperaccumulator plants are a possible solution preventing nickel contamination. They are a natural filter when grown in the roadsides. They are able to take up large quantities of nickel. However, often have a specific habitat and do not grow in climate conditions in the Netherlands.
Olivine does not only take up CO_2, but it also prevents soil acidification. Limestone is currently used as a pH buffer and way to increase the pH of the soil. This can also be done by distributing olivine through the Netherlands where necessary. Adding olivine to the roadsides and asphalt helps against soil acidification. On top of that, it also increases the alkalinity which helps prevent ocean acidification.

Quantity
Olivine has the most potential of being used for enhanced weathering along the roadside and mixed in the asphalt wearing course. The Netherlands has about 130.000 kilometres of hard-surfaced roads (TNO, April 2020). 130.000 times two is 260.000 kilometres of roadside. This gives 260.000 kilometres of potential surface area along the paved roads for olivine to be distributed on. This means a potential surface area of 520 square kilometres, assuming a roadside is 2 meters wide. Olivine has a density of about 3.8 g/cm^3. If a layer of 1 cm of olivine is added to the roadside soil, a potential 19.760.000-ton olivine can be scattered alongside the roads. This means that a potential 658.700-ton CO_2 can be captured per year.

On top of that 95% of asphalt consist of aggregates. There is about 400-ton asphalt per kilometre road for 1 lane. This means a potential of 380-ton olivine per kilometre road for 1 lane. From 130.000 kilometres of road, there is at least one lane for both directions. This means that a potential of at least 380 * 2 * 130.000 = 98.800.000-ton coarse olivine can be integrated with the paved roads in the Netherlands. This would provide a CO_2 reduction of 98.800.000 ton in 30 years. This means that a potential 3.300.000-ton CO_2 can be captured per year.

The calculations for olivine integrated into asphalt is assuming a grain size of 10 µm. However, this is not the case. They need to be ground first by cars driving on the asphalt. Therefore, the real potential CO_2 that can be captured per year will be much less. Data from the pilot in Leek that is currently in progress should give a better indication for the amount of CO_2 that can be captured.

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