



Olivine for Soil Stabilization

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Abstract-The aim of this paper is to review the potential capability of olivine as a new binder for soil stabilization. The recent research shows that using environmental friendly materials for soil stabilization is expanding. The increasing amount of greenhouse gasses (GHG) such as CO₂ has also instigated research into finding environmentally friendly materials for soil stabilization. For quite some time, cement is one of the well-known binders in soil stabilization, but it releases high amount of CO₂, and energy consumption of cement have caused civil engineers to use some other materials or by-products to fully or partially replace cement for soil stabilization. Recently, alkaline activation process in soil stabilization is an interesting option at medium-term to fully eliminate traditional cementitious binders such as cement and lime. Olivine is a well-known material for CO₂ sequestration. Furthermore, the high amount of SiO₂, Al₂O₃ and Fe₂O₃ in olivine could classify this mineral as a pozzolanic material in soil stabilization.

Keywords: Carbonation, olivine, soil stabilization, pozzolanic material, dissolution

Introduction

Using cement in civil engineering comes with several significant disadvantages, the most important of which is the resultant release of carbon dioxide (CO₂) into the atmosphere. CO₂ is the leading greenhouse gas which is an outcome from fossil fuels and human activities, and it causes climate change and global warming. In the 1950s, CO₂ doping grew about 0.7 ppm per year. In the last decade, the CO₂ level significantly increased by 2.1 ppm per year (Hanle, Jayaraman, & Smith, 2004; Ke, Mcneil, Price, & Khanna, 2013). Olivine is a sustainable material that has the potential for use in treating soils as it can capture CO₂ because of the high amount of MgO. The literature indicates the effect of carbonating reactive magnesia for soil stabilization and the positive role of reactive magnesia against cement treated soil (Yi, Liska, Unluer, & Al-Tabbaa, 2013; Yi, Liska, Akinyugha, Unluer, & Al-Tabbaa, 2013).

Soil stabilization

Soil stabilization is one of the oldest and most widespread techniques among the ground improvement methods because construction on soft ground is a main problem in civil engineering. If the ground is

untreated, it is not good enough for the construction, and the bearing capacity or slope failure may occur because of insufficient soil strength (Lee & Karunaratne, 2007).

Stabilized soil is, in general, a composite material that results from a combination and optimization of properties in individual constituent materials. Well-established techniques of soil stabilization are often used to obtain geotechnical materials improved through the addition into soil of such cementing agents (Basha, Hashim, Mahmud, & Muntohar, 2005). The solution of refining these soils in-situ by stabilization often becomes handy, as this has the insinuation of natural resource conservation, reduction in energy usage and carbon dioxide release and increased cost efficiency (Obuzor, Kinuthia, & Robinson, 2012).

Many binder materials possess hardening applications which could potentially be used for the stabilization of soils. Soils with high water content stabilized by traditional mixtures have been commonly used for the construction purpose to enhance bearing capacity, reduce settlement, control shrinking and swelling, and reduce permeability (Miller & Azad, 2000; Åhnberg & Johansson; 2003, Basha, Hashim, Mahmud, & Muntohar, 2005). Although such traditionally chemical stabilizers have been economically attractive, from an environmental point of view, it is more prudent to consider industrial by-products for soil stabilization that are most cost-effective, and not affecting the surrounding soil and groundwater ecology upon treatment. Nevertheless, there are some negative effects of using some of these materials in soil stabilization.

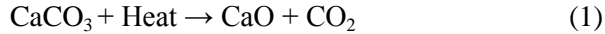
Soil stabilization by cement and lime

Cement is often used as an additive to improve the strength and stiffness of soft clayey soils, and the increase in strength of soft soil by cement is well recognized. Cement treated soils have been developed in the field of geotechnical engineering (Uddin, Balasubramaniam, & Bergado, 1997; Miura, Horpibulsuk, & Nagaraj, 2001; Chew, Kamruzzaman, & Lee, 2004; Horpibulsuk, Rachan, & Suddeepong, 2011). Cement can be used for both modification and stabilization purposes. The addition of a few percentages by weight of cement has shown its success to better control the workability during compaction, and significant cost savings over the removal and replacement of filled materials in some projects (Sariosseiri & Muhunthan, 2009). The properties of cement-treated soil can be divided into primary and secondary cementitious materials in the soil cement matrix. The primary cementitious materials formed by hydration reaction are composed of hydrated calcium silicates (C_2SH_x , $C_3S_2H_x$), calcium aluminates (C_3AH_x , C_4AH_x), and hydrated lime $Ca(OH)_2$. A secondary pozzolanic reaction between the hydrated lime and the silica and alumina from the clay minerals leads to the formation of additional calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH) (Chew et al., 2004; Kasama, Zen, & Iwataki, 2007). The reduction in plasticity index (PI) caused by an increasing plastic limit (PL) and soil swelling, and outstanding increase in strength, modulus of elasticity, and resistance against the effects of moisture can be significantly achieved by cement stabilization. The addition of cement increased the optimum water content (OWC) but decreased the maximum dry density (MDD) (Muhunthan & Sariosseiri, 2008; Horpibulsuk et al., 2011).

Lime, CaO or $Ca(OH)_2$, is the burned byproduct of lime stone ($CaCO_3$), which is one of the oldest developed construction materials that is still popularly used to improve fine-grained soils. Today, lime stabilization is extensively used in numerous structures such as highways, railways, airports, embankments, foundation base, slope protection, canal linings, and others (Muhunthan & Sariosseiri, 2008; Wilkinson, Haque, Kodikara, Adamson, & Christie, 2010; Dash & Hussain, 2011). A considerable amount of literature has been published on soil stabilization by lime. On a major study about the chemical stabilization, the researcher investigated the data on the interaction of the clay from the Mirkovo deposit with lime, and he suggested that under the chosen experimental conditions, the increase in strength during the first six months is entirely caused by the initially formed and hardened gelated products of pozzolanic reactions involving mainly the clay minerals (Ref?). A stabilized soil material is obtained with dry unconfined compressive strength (UCS) of the order of

5MPa to 6MPa. The processes causing changes in the phase composition of the calcium hydrosilicates occur at long storage times (Ninov, Donchev, Lenchev, & Grancharov, 2007).

Lime can change the soil plasticity. First, a decrease in the liquid limit (LL) and an increase in the PL result in an important reduction in PI. Reduction in PI facilitates higher workability of the treated soil. Second, a reduction in water content occurs as a result of chemical reaction between soil and lime (Petry & Little, 2002; Barker, Rogers, & Boardman, 2006). Apart from modifying the plasticity and swelling characteristics, lime can stabilize the soils through cementation, visible increasing soil strength and stiffness (Rajasekaran & Narasimha Rao, 2000; Alavéz-Ramírez, Montes-García, Martínez-Reyes, Altamirano-Juárez, & Gochi-Ponce, 2012). The strength of lime-treated soils is primarily dependent on the dissolved SiO₂ and Al₂O₃ available for pozzolanic reactions, as well as on the existing amounts of Ca²⁺ and OH⁻. Once the ions Ca²⁺ and OH⁻ are fully consumed, the pH drops, and the pozzolanic reactions cease, unless the amounts of Ca²⁺ and OH⁻ are restored to the soil lime-water system (Barker et al., 2006; Consoli, Lopes, Prietto, Festugato, & Cruz, 2011). However, the lime-treated soil shows a complex behavior that is affected by several factors such as the physicochemical properties of the soil, porosity, and the lime content at the time of compaction (Pedarla, Chittoori, Puppala, Hoyos, & Saride, Sireesh, 2010). Cement and lime production involves CO₂ emission. The cement industry produces 5% of global man-made CO₂ emissions, of which 40% and 50% are from burning fuel and chemical process, respectively. The rests are divided between transport and electricity uses (The Cement Sustainability Initiative, 2002). This emission is a contributing factor to the significant global warming expected in future decades. For example in 2010, the China cement output was 1.9 gigatonnes, which accounted for 56% of the world cement production. The Total CO₂ emissions from the Chinese cement production can therefore exceed 1.2 gigatonnes (Ke et al., 2013). CO₂ is emitted from the calcination process of limestone, from combustion of fuels in the kiln, and from power generation. In addition, CO₂ is formed by calcination, which can be expressed by Equation 2.1. According to the equation, 1 kg of CaCO₃ can release 0.44 kg of CO₂ (Worrell, Price, Martin, Hendriks, & Meida, 2001).



$$1\text{kg} \quad \quad 0.56 \text{ kg} + 0.44 \text{ kg}$$

Using magnesium oxide in soil stabilization

Soil stabilization may be a technique introduced several years ago with the main purpose to render the soils capable of meeting the necessities of the particular engineering projects (Kolias, Kasselouri-Rigopoulou, & Karahalios, 2005). Stabilized soil is a composite material that results from the combination and optimization of properties in individual constituent materials. Well-established techniques of soil stabilization are typically used to obtain geotechnical materials that are improved by adding into soil of such cementing agents as Portland cement, lime, and asphalt. The replacement of natural soils, aggregates, and cement with solid industrial by-product are extremely captivating (Basha et al., 2005). Previous studies show the effects of using Mg oxide for soil stabilization, for example, the use of Mg hydroxide to stabilize the swelling clay. The results concluded that the Mg-hydroxide is absorbed by swelling clays both on their external and internal surfaces, whereas it is adsorbed on the external surface by non-swelling clays. The internally adsorbed phase of Mg-hydroxide forms an ill-defined interlayer of brucite to retard swelling, whereas the external phase covers the particles drastically to modify their surface properties (Xeidakis, 1996).

The study indicated that the principal forces concerned in the process are believed to be physical adsorption on the external surface, and a few chemical bonding, largely in the inner surface. Furthermore, cementation occurs because of crystallization and, in the long term, some pozzolanic reactions occur. Internal adsorption of the Mg-hydroxide is postulated to be in the shape of completely charged mono- and/or small polymers, and it is chiefly diffusion controlled. Given that

Mg-hydroxide is internally adsorbed by swelling clays whereas Ca-hydroxide (lime) is not, and also the Mg Ca-clay aggregates are more stable than the Ca-clay or the Mg-one, the mixture of the two hydroxides might provide higher results in soil stabilization than hydroxide alone (Xeidakis, 1996). Another study showed the effect of a low grade MgO on the stability of contaminated soil. The investigation showed that the contaminated soil is stabilized with a low grade MgO, independent of the amount of stabilizer used, and a pH close to 9.2, that is controlled by the solubility of the Mg(OH)₂ (García et al., 2004). In 2010, the investigation about the sustainable material for soil stabilization indicated that the industrial by-products, specifically GGBS, PFA, and cement kiln dust (CKD), and innovative materials such as reactive magnesia and zeolite, clearly have various sustainability benefits over PC in terms of reduced environmental impacts and enhanced technical and durability performances. The stabilization of gravelly sand and clayey silt with a range of PC-blended binders using the above materials showed that all these materials can act as partial replacement for PC in ground improvement applications, which rely on the dosage applied and/or curing time that provided higher strengths (Jegandan, Al-Tabbaa, Liska, & Osman, 2010).

Another study has looked at the properties of the two kinds of soil with different blends and contents of GGBS, lime, MgO, and PC. The investigation has focused on the effect of mixed MgO and GGBS and compared the result by using PC and GGBS-lime mixture on soil stability. The final outcome of this research concluded that the UCS results showed that GGBS-MgO was more extreme than GGBS-lime for soil stabilization with an optimum MgO content in the range of 5% to 20%; also the 28 days UCS value of MgO-GGBS are up to four times higher than mixed PC (Y. Yi, Liska, & Al-Tabbaa, 2014). The recent study in 2013 mentioned the effect of carbonating magnesia for soil stability. The study concluded the effect of carbonated reactive magnesia on the soil stability compared with PC blended in soil. Results showed the treated soil by reactive carbonated magnesia after a few hours has the same stability of 28 days of soil stabilized by PC. The main products of reactive magnesia carbonated are nesquehointe and hydromagnesite-dypingite that are responsible in soil stability (Yaolin, Martin, Cise, & Abir, 2013; Yi, Liska, Unluer, & Al-Tabbaa, 2013).

Olivine characterization

Olivine with the formula (Mg,Fe)₂SiO₄ is a magnesium iron silicate. It is a prevalent mineral within the Earth's subsurface and is usually found in mafic to ultramafic igneous rocks. It is found less commonly in marbles and some alternative metamorphic rock types (Jesa, 2011). The ratio of magnesium to iron can vary in any proportion from pure Mg₂SiO₄ (fosterite) through to pure Fe₂SiO₄ (fayalite). Olivine can exist with colours ranging from yellowish green, olive green, greenish black and reddish brown with densities from 3.27 to 3.37 and averaging 3.32 g/cm³ (Barthelmy, 2010). Table 1 shows the nominal chemistry and physical properties of olivine, which, according to chemical composition, consists of approximately 45% to 49% of MgO.

Table 1: Physical properties of olivine

MgO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	LOI
48.28%	40.32%	8.9%	1.37%	1.13%

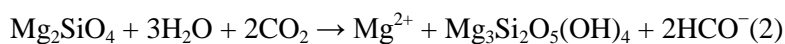
Olivine worldwide distribution

Olivine is found all over the world: India, Myanmar, Egypt, Pakistan, South Africa, Russia, Norway, Sweden, Germany, France, Brazil, Mexico, Ethiopia, China, Australia, and the USA. As early as 1500 BC Egyptian pharaohs mined olivine on Zabargad Island in the Red Sea. Olivine can be detected in the green beaches in Hawaii as well as in meteorites on Mars and Moon (“What is Olivine,” 2013). In Malaysia, according to its geology, there is a possibility of olivine being mined. According to a study

of the Tawau geological heritage area located in the eastern part of Semporna Peninsula in Sabah, West Malaysia, volcanic rocks of the andesite-dacite association form the major mountainous backbone in this area. The rocks contain plagioclase, olivine, hornblende phenocrysts, clinopyroxene, and magnetite microcrystals (Tahir, Musta, & Rahim, 2010). There is every possibility of surface mining the substantial amount of olivine that exists here. Alternatively in tropical areas, the great advantage of this is the fast weathering in tropical areas (Schuiling & Praagman, 2011).

Olivine dissolution

Dissolution and hydrolysis are the results of reactions with acids. Hydrolysis occurs as the transformation of silicate and carbonate minerals into new minerals. In this process, there is total dissolution of the original rock leaving no solid residue (Kayar, 2011). It can be generally explained that olivine dissolution happens when carbonate saturation is attained in the fluid stage, resulting in the precipitation of magnesite, and summarized as follows (Dufaud, Martinez, & Shilobreeva, 2009):



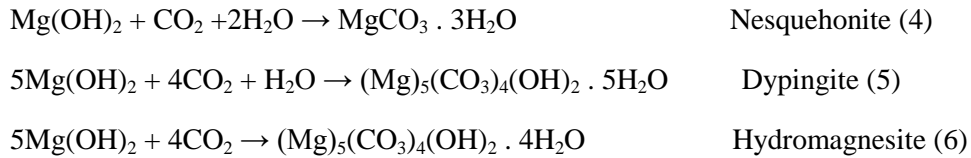
Earlier research findings on the description of the dissolution rate of olivine at low temperature can be extended to higher temperature, which could contain its behaviour as a function of pH, in the presence of CO_2 , and at $\text{pH} \leq 5$ (at 120°C). Dissolution rates have been found to be two times greater than those without CO_2 at the same pH. Citric acid, another ligand previously studied in the literature, also shows a dissolution improvement effect (Hänchen, Prigiobbe, & Storti, 2006). As a result, certain scholars have pointed out that sorption of inorganic carbon type to surfaces can affect dissolution performance for Fe oxides and Ca or Mg silicates. Even at alkaline conditions; silicate dissolution rates demonstrate only an insignificant or at best weak condition on PCO_2 when pH is held constant. For example, the liberation of Ca and Mg from diopside during dissolution decreased slightly or not at all for $\text{PCO}_2 >$ atmospheric (Brantley, 2008).

Many factors affect the dissolution rate of olivine, and some of the most important factors are: the grain size, temperature, solution chemistry (pH, concentration of carbonate, magnesium, silica, organic acids, ionic strength), and the formation of the coating on the grains (Veld, Roskam, & Enk, 2008). Mineral carbonation, that includes the reaction of Mg-rich minerals with CO_2 to produce geologically stable mineral carbonates, has been proposed as a promising CO_2 capturing technology.

Potential of using olivine for soil stabilization

Regarding the chemical properties of olivine as shown in Table 1, olivine is the major source of magnesium oxide (MgO) which makes up to between 45% to 49% by weight. Prior research has demonstrated that magnesium oxide can be successfully utilized for soil stabilization, for example, the use of Magnesium hydroxide to stabilize swelling clay (Xeidakis, 1996). Another investigation studied how a low grade MgO affected the stability of contaminated soil, and the results showed that the contaminated soil was successfully stabilized with the low grade MgO (García et al., 2004). A significant study conducted in 2010 addressed the use of sustainable materials for soil stabilization. The study investigated the effect of mixing industrial by-products with innovative materials such as reactive magnesia and zeolite. These were demonstrated to clearly show a variety of sustainability benefits over PC in terms of reduced environmental impacts and enhanced technical and durability performance (Jegandan et al., 2010). A recent study in 2013 investigated the effects of carbonating magnesia on soil stabilization by comparing it with PC blended in soil. The results showed that soil treated with reactive carbonated magnesia after a few hours had the same stability of soil stabilized by PC after 28 days. The main reaction products of carbonated magnesia responsible for the increased stability were nesquehointe and hydromagnesite-dypingite (Yi, Liska, Unluer, & Al-Tabbaa, 2013). The formulations below show the main products of reactive carbonated magnesium:





Conclusion

The aim of this paper is to review the olivine potentials as a new binder for soil stabilization. Olivine is a sustainable mineral that not only can capture CO₂ from atmosphere through the high amount of MgO, but also the chemical composition of olivine will put this mineral as a pozzolanic material for soil stabilization because of the high amount of SiO₂, Al₂O₃ and Fe₂O₃. The use of olivine as a new mineral for soil stabilization will be a great opportunity for environmental friendly soil stabilization.

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References

- Åhnberg, H., & Johansson, S. (2003). Stabilising effects of different binders in some Swedish soils. *Proceedings of the ICE - Ground Improvement*, 7(1), 9–23.
- Alavéz-Ramírez, R., Montes-García, P., Martínez-Reyes, J., Altamirano-Juárez, D. C., & Gochi-Ponce, Y. (2012). The use of sugarcane bagasse ash and lime to improve the durability and mechanical properties of compacted soil blocks. *Construction and Building Materials*, 34, 296–305.
- Barker, J. E., Rogers, C. D., & Boardman, D. I. (2006). Physio-chemical changes in clay caused by ion migration from lime piles. *Journal of Materials in Civil Engineering*, 18(2), 182–189.
- Barthelmy, D. (2010). Olivine Mineral Data. Retrieved from <http://webmineral.com>
- Basha, E. a., Hashim, R., Mahmud, H. B., & Muntohar, a. S. (2005). Stabilization of residual soil with rice husk ash and cement. *Construction and Building Materials*, 19(6), 448–453.
- Brantley, S. (2008). Kinetics of mineral dissolution. In *Kinetics of water-rock interaction* (pp. 151–210). New York: Springer.
- Chew, S. H., Kamruzzaman, a. H. M., & Lee, F. H. (2004). Physicochemical and Engineering Behavior of Cement Treated Clays. *Journal of Geotechnical and Geoenvironmental Engineering*, 130(7), 696–706.

- Consoli, N. C., Lopes, L. D. S., Prietto, P. D. M., Festugato, L., & Cruz, R. C. (2011). Variables Controlling Stiffness and Strength of Lime-Stabilized Soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(6), 628–632.
- Dash, S., & Hussain, M. (2012). Lime stabilization of soils: reappraisal. *Journal of Materials in Civil Engineering*, 24(6), 707–714.
- Dufaud, F., Martinez, I., & Shilobreeva, S. (2009). Experimental study of Mg-rich silicates carbonation at 400 and 500 °C and 1 kbar. *Chemical Geology*, 265(1-2), 79–87.
- García, M. a, Chimenos, J. M., Fernández, a I., Miralles, L., Segarra, M., & Espiell, F. (2004). Low-grade MgO used to stabilize heavy metals in highly contaminated soils. *Chemosphere*, 56(5), 481–91.
- Hänchen, M., Prigiobbe, V., & Storti, G. (2006). Dissolution kinetics of fosteritic olivine at 90–150° C including effects of the presence of CO₂. *Geochimica et Cosmochimica Acta*, 70(17), 4403–4416.
- Hanle, L., Jayaraman, K., & Smith, J. (2004). CO₂ emissions profile of the US cement industry. *US Environmental Protection Agency*.
- Horpibulsuk, S., Rachan, R., & Suddepong, A. (2011). Assessment of strength development in blended cement admixed Bangkok clay. *Construction and Building Materials*, 25(4), 1521–1531.
- Jegandan, S., Al-Tabbaa, a., Liska, M., & Osman, a. a-M. (2010). Sustainable binders for soil stabilisation. *Proceedings of the ICE - Ground Improvement*, 163(1), 53–61.
- Jesa, T. (2011). Olivine. Retrieved from <http://www.universetoday.com/85005/olivine/>
- Kasama, K., Zen, K., & Iwataki, K. (2007). High-strengthening of cement-treated clay by mechanical dehydration. *Soils and Foundations*. Incomplete!
- Kayar. (2011). All About Chemical Weathering. Retrieved from <http://www.brighthub.com/environment/science-environmental/articles/30585.aspx>
- Ke, J., Mcneil, M., Price, L., & Khanna, N. Z. (2013). Estimation of CO₂ Emissions from China's Cement Production : Methodologies and Uncertainties Methodologies and Uncertainties. *Energy Policy*, 57, 172–181.
- Kolias, S., Kasselouri-Rigopoulou, V., & Karahalios, A. (2005). Stabilisation of clayey soils with high calcium fly ash and cement. *Cement and Concrete Composites*, 27(2), 301–313.
- Lee, S. L., & Karunaratne, G. P. (2007). Treatment of soft ground by Fibredrain and highenergy impact in highway embankment construction. *Proceedings of the ICE - Ground Improvement*, 11(4), 181–193.
- Miller, G. a., & Azad, S. (2000). Influence of soil type on stabilization with cement kiln dust. *Construction and Building Materials*, 14(2), 89–97.
- Miura, N., Horpibulsuk, S., & Nagaraj, T. (2001). Engineering behavior of cement stabilized clay at high water content. *Soils and Foundations*, 41(5), 33–45.

- Muhunthan, B., & Sariosseiri, F. (2008). *Interpretation of geotechnical properties of cement treated soils*. Washington: Washington State Transportation Center (TRAC).
- Ninov, J., Donchev, I., Lenchev, A., & Grancharov, I. (2007). Chemical stabilization of sandy-silty illite clay. *Journal of the University of Chemical Technology and Metallurgy*, 42(1), 67–72.
- Obuzor, G. N., Kinuthia, J. M., & Robinson, R. B. (2012). Soil stabilisation with lime-activated-GGBS—A mitigation to flooding effects on road structural layers/embankments constructed on floodplains. *Engineering Geology*, 151, 112–119.
- Pedarla, A., Chittoori, S., Puppala, A. J., Hoyos, L. R., & Saride, Sireesh, S. (2010). Influence of Lime Dosage on Stabilization Effectiveness of Montmorillonite Dominant Clays. *Advances in Analysis, Modeling & Design, GeoFlorida 2010*: 767–776.
- Petry, T. M., & Little, D. N. (2002). Review of Stabilization of Clays and Expansive Soils in Pavements and Lightly Loaded Structures—History, Practice, and Future. *Journal of Materials in Civil Engineering*, 14(6), 447–460.
- Rajasekaran, G., & Narasimha Rao, S. (2000). Strength characteristics of lime-treated marine clay. *Proceedings of the ICE - Ground Improvement*, 4(3), 127–136.
- Sariosseiri, F., & Muhunthan, B. (2009). Effect of cement treatment on geotechnical properties of some Washington State soils. *Engineering Geology*, 104(1-2), 119–125.
- Schuiling, R., & Praagman, E. (2011). Olivine Hills: Mineral Water Against Climate Change. In S. D. Brunn (Ed.), *Engineering Earth SE - 122* (pp. 2201–2206). Springer Netherlands.
- Tahir, S., MUSTA, B., & Rahim, I. (2010). Geological heritage features of Tawau volcanic sequence, Sabah. *Bulletin of the Geological Society of Malaysia*, 56, 79–85.
- The cement sustainability initiative. (2002). *World Business Council for Sustainable Development*. Retrieved from http://ficem.org/multimedia/2010/cambio10/HOWARD_KLEE_CSI.pdf.
- Uddin, K., Balasubramaniam, A. S., & Bergado, D. T. (1997). Engineering behaviour of cement-treated Bangkok soft clay. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, 28(1), 89–119.
- Veld, H., Roskam, G., & Enk, R. Van. (2008). *Desk study on the feasibility of CO2 sequestration by mineral carbonation of olivine*. Netherlands. TNO Bullt Enviroment and Geosciences. Retrieved from http://wijzijn.europamorgen.nl/9353000/1/j4nvgs5kjg27kof_j9vvhjakykcuezg/vi2a93c761zx/f=/blg18827.pdf
- What is Olivine? (2013). Retrieved from <http://olivineinc.com/company/what-is-olivine/>
- Wilkinson, A., Haque, A., Kodikara, J., Adamson, J., & Christie, D. (2010). Improvement of problematic soils by lime slurry pressure injection: Case Study. *Journal of Geotechnical and Geoenvironmental Engineering*, 136(10), 1459–1468.
- Worrell, E., Price, L., Martin, N., Hendriks, C., & Meida, L. O. (2001). Carbon dioxide emissions from the global cement industry. *Annual Review of Energy and the Environmen*, 21, 303–329.

- Xeidakis, G. (1996). Stabilization of swelling clays by Mg (OH) 2. Changes in clay properties after addition of Mg-hydroxide. *Engineering Geology*, 44(1-4), 107–120.
- Yi, Y. ., Liska, M., Unluer, C., & Al-Tabbaa, A. (2013). Initial investigation into the carbonation of MgO for soil stabilisation. In *Proceedings of 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris* (Vol. 5, pp. 2641–2644). Retrieved from http://www.cfms-sols.org/sites/all/lic/pages/download_pdf.php?file=2641-2644.pdf
- Yi, Y., Liska, M., Akinyugha, A., Unluer, C., & Al-Tabbaa, A. (2013). Preliminary laboratory-scale model auger installation and testing of carbonated Soil-MgO columns. *Geotechnical Testing Journal*, 36(3), 1–10.
- Yi, Y., Liska, M., & Al-Tabbaa, A. (2014). Properties of two model soils stabilised with different blends and contents of GGBS, MgO, lime and PC. *Journal of Materials in Civil Engineering*, 26(2), 267–274.
- Yi, Y., Liska, M., Unluer, C., & Al-Tabbaa, A. (2013). Carbonating magnesia for soil stabilization. *Canadian Geotechnical Journal*, 50(8), 899–905.