UNIVERSITI PUTRA MALAYSIA

UTILIZATION OF OLIVINE FOR SOIL STABILIZATION

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FK 2016 12

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By

MOHAMMAD HAMED FASIHNIKOUTALAB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

February 2016

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DEDICATION

This thesis is dedicated to my parents and my sister.

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of requirement for the Degree of Doctor of Philosophy

UTILIZIATION OF OLIVINE FOR SOIL STABILIZATION

By

MOHAMMAD HAMED FASIHNIKOUTALAB

February 2016

Chairman : Professor Bujang Kim Huat, PhD
Faculty : Engineering

Soil stabilization is a common technique used for ground improvement. This promising technique uses cement and lime for construction purposes to enhance soil stability. However, binder production increases carbon dioxide (CO_2) in the atmosphere per year. Therefore, sustainable materials for soil stabilization that are cost effective and not damaging to the surrounding soil upon treatment should be identified. Olivine [$(Mg,Fe)_2SiO_4$] is a sustainable material that can naturally capture CO_2 in the atmosphere to form carbonated mineral. Furthermore, the chemical compositions of olivine are high amounts of magnesium oxide (MgO) and silicon oxide (SiO), as well as an adequate amount of silicon dioxide (SiO_2), which make olivine a good candidate for soil stabilization in terms of hydration and pozzolanic reaction.

This study aimed to address some issues about the use of olivine as a new sustainable material for soil stabilization through CO_2 sequestration and in the presence of sodium hydroxide (NaOH), an alkaline activator. To identify the applicability of olivine-treated soil, the unconfined compressive strength (UCS), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), Fourier transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD) analyses were carried out on pure soil and olivine-treated soil before and after carbonation and in the presence of NaOH. The four specific objectives of this study are as follows. First is to investigate the mechanical and engineering behaviors of olivine-treated soil with different olivine contents at different curing times. Second is to determine the function of the carbonated olivine on the stability of soil at two different carbon pressures in different carbonation periods through the physical model in the laboratory. Third is to evaluate the effect of olivine in the presence of NaOH on soil stability and to identify the role of olivine as a source binder and NaOH as an activator of silicon and aluminum of olivine for soil stabilization at different curing times. Fourth and last is to examine the beneficial function of NaOH on the stability of carbonating olivine-treated soil at two different CO_2 pressures with different carbonation periods based on geotechnical and microstructure analyses. In the first stage, mechanical and microstructure results confirmed that olivine changed the engineering properties of soil and increased soil stability up to

1.4 times more than untreated soil. In the second stage, the UCS of 20% olivine carbonated increased the strength of soil at high CO_2 pressure after long carbonation period. The SEM analysis of 20% olivine-treated soil indicated that carbonated olivine decreased the soil discontinuity as a result of hydration and carbonation of MgO to produce $Mg(OH)_2$ and $MgCO_3$. The XRD analysis confirmed this indication. In the third stage, the results presented that the 20% olivine treated soil in the presence of 10 M NaOH increased the UCS of the soil after long curing time.

Moreover, the SEM analysis confirmed the dissolution of olivine through the NaOH to have a homogenous soil structure. The EDX analysis demonstrated that when the Na/Al and Si/Al ratios increased, the soil strength also increased. The FTIR analysis showed the peaks of Si-O-Al, Si-O, Al-O, C-O, -OH, and H-O-H to establish the functions of NaOH and olivine as an activator and good source binder, respectively. In the final stage, carbonation of olivine-treated soil in the presence of NaOH at different pressures and different carbonation periods increased the strength of 20% olivine-treated soil to 6MPa. The following results were obtained: First, the use of 20% of olivine as a sustainable material for soil stabilization is noteworthy but it cannot sufficiently increase the strength of the soil. Second, the carbonation of olivine-treated soil increased the soil mechanical properties. Third, olivine acted as a source binder in the presence of NaOH to stabilize the soil. Finally, when the potential capacity of olivine carbonation in the presence of NaOH increased, the soil strength increased. This research discover that olivine can be used as a new stabilizer for soil improvement

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Abstrak tesis yang telah dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENGGUNAAN OLIVIN BAGI PENSTABILAN TANAH

Oleh

MOHAMMAD HAMED FASIHNIKOUTALAB

Februari 2016

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Penstabilan tanah adalah salah satu teknik paling biasa dalam kalangan kaedah pembaikan tanah. Simen dan kapur telah biasa digunakan dalam teknik berpotensi ini untuk tujuan pembinaan bagi meningkatkan kestabilan tanah. Walau bagaimanapun, peningkatan penggunaan pengeluaran pengikat ini berterusan menambahkan lebih banyak CO_2 ke atmosfera setiap tahun. Ia adalah lebih berhemat untuk mempertimbangkan beberapa bahan mampan bagi penstabilan tanah paling kos efektif dan akan kurang memberi kesan kepada tanah sekitarnya semasa rawatan. Olivin $(Mg, Fe)_2SiO_4$ adalah bahan mampan yang terkenal bagi menangkap CO_2 secara semula jadi melalui atmosfera untuk membentuk mineral berkarbonat. Tambahan pula, komposisi kimia olivin dengan jumlah yang tinggi magnesium oksida (MgO) dan silikon oksida dan (SiO_2) menjadikannya sebagai pilihan yang baik bagi penstabilan tanah dari segi penghidratan dan reaksi pozzolana.

Objektif kajian ini adalah untuk memberi pencerahan terhadap perbahasan ini melalui pengujian olivin sebagai bahan mampan baru bagi penstabilan tanah melalui pengasingan CO_2 secara individu dan juga dengan kehadiran pengaktif alkali natrium hidroksida (NaOH). Untuk mengenal pasti kesesuaian tanah yang dirawat olivin, ujian kekuatan mampatan tak terkurung (UCS), SEM/EDX, FTIR dan XRD telah dijalankan di tanah suci dan tanah yang dirawat olivin sebelum dan selepas pengkarbonatan dan juga dengan kehadiran NaOH.

Skop kajian ini adalah untuk pertama menyiasat tingkah laku mekanikal dan kejuruteraan tanah yang dirawat olivin dengan kandungan olivin yang berbeza pada masa pengawetan yang berbeza. Kedua, ia menentukan peranan olivin berkarbonat terhadap kestabilan tanah pada dua tekanan karbon yang berbeza dalam tempoh pengkarbonatan berbeza melalui model fizikal di makmal. Ketiga, ia menilai kesan olivin dengan kehadiran NaOH terhadap kestabilan tanah, untuk mengenal pasti peranan olivin sebagai sumber pengikat dan NaOH sebagai penggerak untuk mengaktifkan silikon dan aluminium olivin bagi penstabilan tanah pada masa pengawetan yang berbeza. Akhir sekali, ia menyiasat peranan benefisial NaOH terhadap kestabilan pengkarbonatan tanah yang dirawat olivin pada dua tekanan CO_2

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yang berbeza dengan tempoh pengkarbonatan yang berbeza berdasarkan analisis geoteknikal dan mikrostruktur.

Pada peringkat pertama keputusan mekanikal dan mikrostruktur mengesahkan bahawa olivin telah mengubah ciri-ciri kejuruteraan tanah dan juga meningkatkan kestabilan tanah. Pada peringkat kedua, UCS sebanyak 20% olivin berkarbonat meningkatkan kekuatan tanah pada tekanan CO_2 yang tinggi selepas tempoh pengkarbonatan panjang. Selanjutnya, analisis SEM sebanyak 20% tanah yang dirawat olivin menunjukkan bahawa olivin berkarbonat mengurangkan ketakselanjaran tanah lebih akibat penghidratan dan pengkarbonatan MgO untuk menghasilkan $Mg(OH)_2$ dan $MgCO_3$, juga analisis XRD mengesahkan penunjuk ini. Pada peringkat ketiga, keputusan menunjukkan bahawa 20% tanah yang dirawat olivin dengan kehadiran 10molar NaOH meningkatkan UCS tanah selepas tempoh pengawetan panjang. Selain itu, analisis SEM mengesahkan pelarutan olivin melalui NaOH untuk mendapatkan struktur tanah homogen, dengan itu analisis EDX menunjukkan bahawa peningkatan nisbah Na/Al dan Si/Al akan meningkatkan kekuatan tanah, analisis FTIR juga menunjukkan puncak Si-O-Al, Si-O, Al-O, C-O, -OH dan H-O-H untuk mewujudkan peranan NaOH sebagai penggerak dan olivin sebagai sumber pengikat yang baik. Pada peringkat akhir, pengkarbonatan tanah yang dirawat olivin dengan kehadiran NaOH pada tekanan yang berbeza dan tempoh pengkarbonatan berbeza meningkatkan kekuatan 20% tanah yang dirawat olivin kepada 6MPa.

Hasil menunjukkan; pertama menggunakan 20% olivin sebagai bahan mampan bagi penstabilan tanah patut diberi perhatian tetapi ia tidak boleh meningkatkan kekuatan tanah begitu baik. Kedua, pengkarbonatan tanah yang dirawat olivin meningkatkan ciri-ciri mekanikal tanah. Ketiga, olivin bertindak sebagai sumber pengikat dengan kehadiran NaOH bagi menstabilkan tanah. Akhir sekali, meningkatkan kapasiti potensi pengkarbonatan olivin dengan kehadiran natrium hidroksida meningkatkan kekuatan tanah. Kajian ini penting kerana ia mengesahkan olivin sebagai penstabil baru yang boleh digunakan untuk pembaikan tanah.

ACKNOWLEDGEMENTS

First of all, my utmost gratitude goes to Allah. I owe my gratitude to my beloved parents and my sister for their support, help, and love.

I would like to acknowledge to my supervisors, Prof. Bujang Kim Huat, Dr. Afshin Asadi, Dr. Richard Ball, and Dr. Haslinda Nahazanan for their encouragement, patience, supervision, guidance and support from the initial to the final level and completion of this thesis.

I sincerely thanks to, the University Putra Malaysia and Fundamental Research Grant Scheme (FRGS/1/2015/TK01/UPM/01/2) entitled “sustainable soil stabilization by olivine and its mechanisms” funded by Ministry of Higher Education in Malaysia (Project ID 93474-135837) for financial support of this research.

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I certify that a Thesis Examination Committee has met on 25 February 2016 to conduct the final examination of Mohammad Hamed Fasihnikoutalab on his thesis entitled "Utilization of Olivine for Soil Stabilization" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

GHG	Greenhouse gases
ASTM	American Society for Testing and Materials
CSH	Calcium silicate hydrates
CAH	Calcium aluminate hydrates
MOC	Magnesium oxychloride
MOS	Magnesium oxysulfate
MAP	Magnesium phosphate cement
XRD	X-ray diffractograms
SEM	Scanning electron microscopy
EDX	Energy-dispersive X-ray spectroscopy
GGBS	Ground granulated blast furnace slag
POFA	Palm oil fly ash
CKD	Cement kiln dust
CASH	Calcium aluminate silicate hydrate
UCS	Unconfined compressive strength
MDD	Maximum dry density
OWC	Optimum water content
S	Soil
SO_BT	Soil-Olivine $_{(dosage)}$-Curing time
LL	Liquid limit
PL	Plastic limit
PI	Plasticity index
MSH	Magnesium silicate hydrate
$C_{T,P}SO_B$	Carbonated $_{(time,\ pressure)}$ Soil-Olivine $_{(dosage)}$
CSI	Cement Sustainability Initiative
AS	Alkaline activated treated soil

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Soil stabilization has always been an important part of civil engineering as it defines the integrity of any subsequent structure that is erected. Natural soil is a complex and variable material. Soil offers great opportunities for skillful use as an engineering material because of its low cost and worldwide availability. However, most soils are not suitable for construction or engineering purposes. Several methods are available for application to different types of soils depending on their properties, composition and characteristics. As a general rule, some soils alone do not have sufficient strength. Consequently, the use of some materials as additives in the soil body results in strengthening and stabilization of the soil. Cement is a widely used material for soil stabilization.

Average annual growth in consumption is estimated to be 1.4%, 1.6%, and 2.4% for coal, oil, and natural gas, respectively. These anthropogenic activities are expected to increase greenhouse gas (GHG) emissions to more than 70% between 2000 and 2030, amounting to 38 billion tons of energy-related CO_2 emissions worldwide in 2030, resulting in global climate modification (Ke, Mcneil, Price, & Khanna, 2013). The growing demand is predicted to lead to a need for an increased use of numerous fossil fuels by a mean of 1.7% per year until 2030 (Birol, 2002).

Furthermore, early examples of research into climate change included estimations of atmospheric concentrations levels of 430 ppm to 530 ppm CO_2 by 2100, which will require cuts in GHG emissions and restrictions on cumulative CO_2 emissions in both the medium and long term. The majority of developments reaching 430 ppm to 480 ppm CO_2 by 2100 are linked with GHG emissions reductions of over 40% to 70% by 2050 compared with 2010 (Edenhofer et al., 2014). Figure 1.1shows that the two sectors produced nearly two-thirds of global CO_2 emission in 2010.

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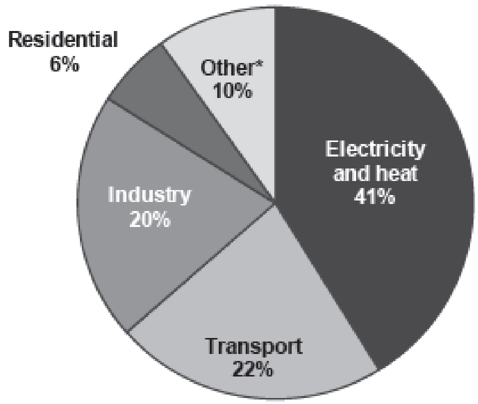

Figure 1.1. **World CO_2 emission by sector in 2010 (Source: IEA, 2012)**
Note: Other includes commercial/public services, agriculture/forestry, fishing, energy industries other than electricity and heat generation, and other emissions not specified elsewhere

Recently, studies show the use of some materials, such as MgO, as replacements of cement for soil stability (Åhnberg & Johansson, 2003, Jegandan, Al-Tabbaa, Liska, & Osman, 2010). The investigations show that the optimum percentage of using MgO mixed with cement has the same properties as pure cement. Furthermore, mixing with some waste materials in this combination has good results.

According to American Society for Testing and Materials (ASTM), some waste materials can be pozzolanic materials and can stabilize the soil. The use of MgO as an additive in the soil has many benefits, including reducing the amount of cement in soil, strengthening the soil, and capturing CO_2 in the atmosphere, soil, and rain. Through the use of CO_2 absorption methods, adsorption on minerals (mineralization) has become a promising technology for CO_2 capturing because minerals can react with CO_2 and form stable carbonates, leading to permanent CO_2 sequestration; this mineral carbonation is an essential process of chemical weathering by alkaline earth minerals to apply such mineral carbonation to capture CO_2 capture (Kwon, 2011).

Olivine ($(Mg,Fe)_2SiO_4$) is an abundant mineral that can potentially capture CO_2 from the atmosphere. Olivine is made of different ratios of iron to Mg; in general, olivine is common in the outer mantle of the earth creating up to 50% of its composition, as a result olivine is usually found in mafic and ultramafic igneous rocks and in some types of metamorphic rock (Jesa, 2011). Therefore, olivine is the main mineral of the earth that is relatively rare on the earth surface, where it mainly occurs as mantle xenoliths in certain basalt types, in Dunite/Peridotite massifs, or as Phenocrysts in basic volcanic; hence Olivine has an important function not only in the environmental technology, but also in improving soils and buffer acid rain produced by greenhouse gasses (GHG) (Schuiling, 2001).

From an environmental point of view, natural resources and by-products should be considered for soil stabilization. Olivine is a sustainable candidate to control the climate change through CO_2 sequestration. All CO_2 released by burning 1 L of oil react with > 1 L of olivine or 1 M of olivine for 2 M of CO_2 (Schuiling, 2001).

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As a result of CO_2 sequestration through olivine, a stable mineral carbonates is produced. In addition, in accordance with ASTM D5370, olivine can be considered as a pozzolanic material because of the large amount of composition of SiO_2, Fe_2O_3, and Al_2O_3, which can potentially improve the soil strength. Furthermore, the high percentage of MgO in Olivine makes a high potential for hydration and carbonation, contributing to the soil strength.

Olivine is widely distributed around the world. Geological survey of Malaysia shows that there is a large amount of volcanic rocks of the andesite-dacite-basalt in Tawau Mountains in Sabah which is the main source of olivine (Tahir, MUSTA, & Rahim, 2010).

The first stage of this study shows the effect of olivine on the engineering properties, stabilization, and micro structure analysis of olivine-treated soil. The second stage accounts the effect of carbonating olivine on the stability of olivine-treated silt clay soil. The third stage of this study shows the function of an alkaline activator sodium hydroxide (NaOH) and olivine in the stability of silt clay soil. The fourth stage of this research explores the ways in which how carbonation of olivine-treated soil in the presence of NaOH has positive advantages for stabilization of soil.

This study investigates the use of the olivine to stabilize the soil through CO_2 sequestration. Unstable soils are common in Malaysia. Moreover, this study adds alkaline activators such as sodium hydroxide (NaOH) with olivine to contribute to the soil stability and increase the CO_2 sequestration by breaking the chemical bonding of MgO and SiO_2 in olivine through the hydration and carbonation of MgO and releasing of SiO_2 as pozzolanic material. The addition of an activator results in high shear strength, and the climate change can be controlled.

1.2 Problem statement

Unstable soil in Malaysia is a geotechnical problem. Cement and lime are the most widely used stabilizers. However, these materials have some environmental issues because of CO_2 emission in the atmosphere. Therefore, some materials with less damaging effects on the environment for soil stabilization have been studied. From an environmental point of view, it is more prudent to consider natural resources for soil stabilization. Moreover, some waste materials do not only have the ability for soil improvement, but also decrease the soil content on the earth surface. However, some of these by-products could be harmful for the surrounding soils. This study introduces olivine as a new sustainable material for soil stabilization through CO_2 sequestration and shows how olivine can improve the strength of soil matrix.

1.3 Objectives

The main objective of this study is to investigate the effectiveness of olivine as a sustainable material (individually and through alkaline activation technique) for soil stabilization. Thus, the following specific objectives are expected to be addressed throughout this study:

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1. To determine the effect of olivine on some engineering properties and underlying stabilization mechanism of stabilized soil.
2. To identify the strength and underlying stabilization mechanism of carbonated olivine-stabilized soil.
3. To determine the effect of alkaline activation on the strength and underlying mechanism of olivine-treated soil.
4. To determine the effect of carbonation on the strength and underlying mechanism of olivine treated soil in the presence of alkaline activators.

1.4 Organization of this thesis

The chapters of the thesis are organized as follows:

Chapter 2 presents the literature review on soil stabilization by using some traditional binders, by-products, and MgO. This chapter also includes the principle of mineral carbonation, including olivine carbonation and the most important factors of olivine carbonation. Furthermore, this chapter presents the effect of alkaline activation on soil stabilization.

Chapter 3 discusses the effect of different percentages of olivine on some engineering properties and microstructure analysis of olivine-treated soil before carbonation at different curing times.

Chapter 4 describes the effect of carbonating of olivine-treated soil at different carbonation pressures and times on some engineering properties of soil. The study evaluated the microstructure analysis of carbonated olivine-treated soil at high CO_2 pressures and carbonation period.

Chapter 5 explains the effect of alkaline activation on the stability of olivine-treated soil before carbonation at different curing times and after carbonation at different CO_2 pressures and carbonation times on engineering properties and microstructure analysis of soil. This chapter also introduces the olivine as a natural source binder for soil stabilization through the alkaline activation method.

Chapter 6 presents the conclusions of this study and recommendations for future research.

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