BIOMEDIATED SOIL IMPROVEMENT IN THE MITIGATION OF LIQUEFIABLE SANDY SOIL

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DEDICATION

This thesis is dedicated to the entire members of my family for their support, patience and understanding throughout the period of my study.

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ABSTRACT

Soil liquefaction is one of the catastrophic effects that result from earthquakes. It is a phenomenon that occurs when loose, saturated, cohesionless soil loses its strength and stiffness as a result of rapid loading. Several techniques have been employed to mitigate the effects of soil liquefaction. However, these techniques either require high energy for its execution, or the chemical admixtures used may have adverse effects on the environment. Consequently, biocementation via microbial induced carbonate precipitation (MICP) and enzyme induced carbonate precipitation (EICP) was explored as a technique to mitigate soil liquefaction. The bacterial strain used in the MICP process was *Bacillus megaterium*. Meanwhile, a plant-derived urease enzyme was used in EICP. In this study, experimental based research was conducted to examine the feasibility of biocementation in the mitigation of liquefaction in sandy soil. The research is divided into three main phases. The first phase examines the effect of environmental factors (pH, temperature and salt content) on the growth of *B. megaterium*. Test tube tests were conducted to determine the amount of calcium carbonate ($CaCO_3$) precipitates at different cementation reagent concentrations. Based on the test tube test's results, the EICP method of treatment was adopted to continue with the second and third study phases, due to the amount of calcite produced in the process. The second phase evaluates the effectiveness of EICP treatment on sandy soil through a series of unconfined compressive strength (UCS) tests. The effects of factors, such as curing temperature (4, 10, 20, 30, 40 and 50ºC), the concentration of cementation reagent (0.25, 0.5, 0.75, 1.0 and 1.25 M), number of treatment cycles (1, 2 and 3 cycles) and relative density (loose, medium and dense), palm oil fuel ash (POFA) content were examined on the biocemented soil. The third phase evaluates the effect of biocementation on the cyclic resistance of sandy soil, in terms of confining pressure, Cyclic Stress Ratio (CSR) and relative density, through a series of cyclic triaxial tests. The liquefaction potential of treated soils was investigated with respect to the development of excess pore pressure. The optimum environmental growth conditions, in terms of pH, temperature and salt content, were pH 7, 30°C and 1% (w/v) NaCl, respectively. Findings from the test tube tests showed the mass calcium carbonate precipitate increased when the concentration of cementation reagent (CCR) was increased from 0.5-1.0 M; irrespective of the curing period for both MICP and EICP. Findings from the UCS tests showed a linear relationship between UCS values at various cementation reagent concentrations and average calcium carbonate content. Furthermore, the strength of biocemented sandy soil was attributed to not only the calcite content formed within the soil but also the extent of soil density. The increase in cycles of treatment via surface percolation led to higher strength and $CaCO_3$ content, irrespective of CCR. Image analysis, using Image J software, confirms the reduction in the area of pore spaces within the SEM images, with an increase in the number of cycles of treatment. The addition of POFA to the biocemented soil helped in reducing the ammonium content released. Results from the cyclic triaxial test showed that the EICP treatment improved the sand's resistance against the generation of pore water pressure, as indicated by the greater number of cycles required to induce liquefaction. It can be concluded that biocementation via EICP can be an effective method of mitigating liquefaction in sandy soil.

ABSTRAK

Pencairan tanah adalah salah satu kesan bencana yang disebabkan oleh gempa bumi. Ia merupakan fenomena yang berlaku apabila tanah yang longgar, tepu, dan tiada jeleket kehilangan kekuatan dan kekakuannya akibat pembebanan yang pantas. Beberapa teknik telah digunakan untuk mengurangkan kesan pencairan tanah. Walau bagaimanapun, teknik-teknik ini sama ada memerlukan tenaga yang tinggi untuk pelaksanaannya, atau campuran kimia yang digunakan mungkin memberi kesan yang buruk terhadap alam sekitar. Oleh yang demikian, biosementasi melalui pemendakan karbonat yang disebabkan oleh mikrob (MICP) dan pemendakan karbonat yang disebabkan oleh enzim (EICP) boleh digunakan sebagai pendekatan yang mesra alam untuk mengurangkan pencairan tanah. Jenis bakteria yang digunakan dalam proses MICP ialah *Bacillus megaterium*, sementara enzim urease yang berasal dari tumbuhan digunakan dalam proses EICP. Dalam kajian ini, penyelidikan berdasarkan eksperimen telah dijalankan untuk memeriksa ke boleh laksaaan menggunakan biosementasi untuk mengurangkan pencairan di tanah berpasir. Penyelidikan ini terbahagi kepada tiga fasa utama. Fasa pertama mengkaji kesan faktor persekitaran (pH, suhu dan kandungan garam) terhadap pertumbuhan *B. megaterium*. Ujian tabung uji dijalankan untuk menentukan jumlah mendakan kalsium karbonat ($CaCO_3$) pada kepekatan reagen sementasi yang berbeza. Berdasarkan keputusan ujian tabung uji, kaedah rawatan EICP digunakan seterusnya dalam fasa kajian kedua dan ketiga berdasarkan jumlah kalsit yang dihasilkan melalui proses tersebut. Fasa kedua menilai keberkesanan rawatan EICP terhadap tanah berpasir melalui satu siri ujian kekuatan mampatan tidak terkurung (UCS). Kesan faktor-faktor seperti suhu pengawetan (4, 10, 20, 30, 40 dan 50ºC), kepekatan reagen (0.25, 0.5, 0.75, 1.0 dan 1.25 M), bilangan kitaran rawatan (1, 2 dan 3 kitaran) dan ketumpatan relatif (longgar, sederhana dan padat), dan kondungan Abu kelapa sawit (POFA) diperiksa pada tanah yang telah melalui biosementasi. Fasa ketiga menilai kesan biosementasi terhadap ketahanan berkitaran tanah berpasir dari segi tekanan terkurung, Nisbah Tekanan Berkitaran (CSR) dan kepadatan relatif, melalui satu siri ujian paksi tiga berkitaran. Potensi pencairan berlaku pada tanah yang dirawat telah disiasat berkaitan dengan peningkatan tekanan liang yang berlebihan. Keadaan pertumbuhan persekitaran yang optimum dari segi pH, suhu dan kandungan garam, masing-masing adalah pH 7, 30°C dan 1% (w/v) NaCl. Hasil kajian ujian tabung uji menunjukkan jisim mendakan kalsium karbonat meningkat apabila kepekatan reagen sementasi (CCR) dipertingkatkan dari 0.5-1.0 M; tanpa mengira tempoh pengawetan untuk kedua-dua MICP dan EICP. Penemuan dari ujian UCS menunjukkan hubungan linear wujud antara nilai-nilai UCS pada pelbagai kepekatan reagen sementasi dan kandungan purata kalsium karbonat. Tambahan pula, kekuatan tanah berpasir yang melalui biosementasi bukan hanya disebabkan oleh kandungan kalsit yang terbentuk dalam tanah tetapi juga ketumpatan tanah tersebut. Peningkatan kitaran rawatan melalui percolasi permukaan membawa kepada kekuatan dan kandungan $CaCO_3$ yang lebih tinggi, tanpa mengira CCR. Analisis imej, menggunakan perisian Image J, mengesahkan pengurangan luas ruang liang dalam imej SEM, dengan peningkatan bilangan kitaran rawatan. Pengan penambahan POFA terhadap tanah yang melalui biosementasi membantu mengurangkan kandungan ammonium yang dilepaskan. Hasil ujian paksi tiga berkitaran menunjukkan bahawa rawatan EICP meningkatkan daya tahan pasir terhadap penjanaan tekanan air liang, seperti yang ditunjukkan oleh peningkatan jumlah kitaran yang diperlukan untuk mendorong pencairan. Dapat disimpulkan bahawa biosementasi melalui EICP boleh menjadi kaedah yang berkesan untuk mengurangkan pencairan di tanah berpasir.

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LIST OF ABBREVIATIONS

ASTM	-	American Society for Testing and Materials
ATCC	-	American Type Culture Collection
BLAST	-	Basic Local Alignment Search Tool
BS	-	British Standard
CSR	-	Cyclic Stress Ratio
DNA	-	DeoxyriboNucleic Acid
EDX	-	Energy Dispersive X-Ray Spectroscopy
EICP	-	Enzyme induced carbonate precipitation
ELDCS	-	Enterprise Level Dynamic Control System
LVDT	-	Linear Variable Displacement Transducer
MICP	-	Microbially Induced Calcite Precipitation
NCBI	-	National Centre for Biotechnology Information
OD	-	Optical Density
PCR	-	Polymerase Chain Reaction
SEM	-	Scanning Electron Microscope
UCS	-	Unconfined Compressive Strength
USCS	-	Unified Soil Classification System
XRD	-	X-Ray Diffraction
XRF	-	X-Ray Fluorescence
POFA	-	Palm Oil Fuel Ash
PVC	-	Polyvinyl Chloride

LIST OF SYMBOLS

G_s	-	Specific gravity
M	-	Molarity
$CaCO_3$	-	Calcium Carbonate
g/L	-	gram per litre
D_r	-	Relative density
$^{\circ}C$	-	Degree Celsius
σ_d	-	Deviator stress
σ_c	-	Effective confining pressure

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The continuous growth in the human population, urbanisation and industrial development in recent decades has contributed to increased demand for more social amenities. Hence, some of these amenities are being constructed on scarce lands such as low land areas, reclaimed lands and along seas. Such land reclamations are mostly carried out using loose river sand which tends to undergo liquefaction when subjected to significant ground movement (Jia, 2018). Liquefaction is described as a phenomenon that occurs mostly during earthquakes. When the ground is made up of loosely packed sandy soil and is saturated with groundwater, the soil tends to deform under transient, monotonic or repetitive loading in an undrained state. Such movements lead to a sudden reduction in shear strength and stiffness due to an abrupt increase in pore water pressure to a point where the effective stress reaches zero (Kramer, 1996; Kumari and Xiang, 2017). Hence, infrastructures constructed on liquefiable soils are prone to damage during earthquakes (Aygün *et al.*, 2010; Montoya *et al.*, 2013). The effects of earthquake-induced liquefaction on existing structures were introduced to geotechnical engineers following two main earthquakes in the year 1964 in Niigata (Japan) and Alaska (the USA). After which, extensive research has been conducted on the liquefaction mechanism, potential evaluation mechanism, mitigation methods, predication etc. Figure 1.1 illustrates the possible damages caused by soil liquefaction.

(a) (b)

Figure 1.1 Digital images showing damages caused by soil liquefaction (a) Failure of apartment buildings by tilting in Niigata due to liquefaction (b) Failure of roads leading to a Government Hill elementary school in Alaska due to liquefaction (Source: National Geophysical Data centre cited by Agaiby and Ahmed (2016))

On the other hand, the conventional soil improvement techniques to reduce the effects of soil liquefaction include preloading to achieve consolidation, soil densification using mechanical energy, incorporation of chemical admixtures and grouting using synthetic materials like epoxy, sodium silicate and cement (Ferdous *et al.,* 2020; Karol, 2003; Zullo *et al.,* 2020). However, many of these artificial grouts and chemicals invariably affect the environment, hence, should be used with caution (Gomez *et al.,* 2016; Gowthaman *et al.,* 2019b; Jayanthi and Singh, 2016).For instance, cement production alone is estimated to contribute between 5% to 7% of the global emissions of carbon dioxide (Benhelal *et al.,* 2013; Jos and Maenhout, 2016). Consequently, many countries are aiming to reduce their carbon emissions including the UK which targets to reduce its carbon emissions up to 80% (against the 1990 baselines) by the year 2050. Such goals pose significant challenges and opportunities to sectors involved in the transition towards lower consuming economies as the use of cementitious materials is widespread in conventional methods for ground improvement. Hence, advancements in ground technology are needed to ensure lower carbon usage, less energy demand, in addition to eco-friendly practices. A possible way of achieving an environmentally friendly soil improvement technique is to consider the roles of microbial processes in rocks and soils.

Thus far, the biological-based method is a promising and eco-friendly technique used to enhance the geomechanical characteristics of soils either through microbially induced calcite precipitation (MICP) and enzyme induced calcite precipitation (EICP). Both methods are the most extensively-researched areas in the field of geotechnical engineering in the last decade (Bhutange and Latkar, 2020; Kahani *et al.,* 2020; Kong *et al.,* 2019; Sun *et al.,* 2020; Thomas O'Donnell and Kavazanjian, 2015). Both the MICP and EICP processes produce a bio-cemented soil matrix through a series of biogeochemical reactions. The reactions include urea hydrolysis, sulfate reduction and denitrification (Wang *et al.,* 2017; Zhu and Dittrich, 2016). EICP and MICP can be distinguished based on their source of urease which catalyses the hydrolysis reaction. EICP utilises plant-derived urease enzyme mostly extracted from jack bean (*Canavalia ensiformis*) (Krajewska, 2018). While MICP uses urease enzyme secreted from ureolytic microorganisms. The most common bacterial species used in MICP include *Sporosarcina pasteurii* and *Bacillus megaterium* (Castro-Alonso *et al.,* 2019; Zhu and Dittrich, 2016). However, both methods produce calcium carbonate ($CaCO_3$) which is responsible for cementing soil particles together, to improve strength, stiffness and to reduce the permeability of the soil (Dovom *et al.,* 2020; Ghosh *et al.,* 2019; Peng and Liu, 2019). Having said that, the potential applications of biomediated soil improvement include dust control, liquefaction reduction, erosion control and crack repair, increase slope stability and general strength improvement of various soils (Ghasemi *et al.,* 2019; Liu, Wang, *et al.,* 2020; Salifu *et al.,* 2016; Simatupang and Okamura, 2017).

Apart from the aforementioned methods, interest in soil improvement via calcite precipitation was triggered when Kucharski *et al*. (1996) evaluated the effects of calcite *in-situ* precipitation system on the mechanical properties of calcareous and silica sand. The first publication in geotechnical engineering explaining the concept of biocementation was by Mitchell and Santamarina (2005), where the authors identified and demonstrated its potential role in soils and rocks, stimulating interest in this aspect of multidisciplinary research. However, the importance of this research area was put back in limelight in the 21^{st} century by the US National Research Council (NRC, 2006). Since then, biological-based systems for soil improvement have been widely researched in geotechnical engineering. The relevance of the research area can be ascertained based on the number of publications by year when the 'microbial induced carbonate precipitation' and "enzyme induced carbonate precipitation" keywords were searched in the web of science database. Figure 1.2 represents the trend of publications, in which the increasing interests of researchers to explore alternative methods to the conventional techniques in improving the properties of various soils is revealed. It shows MICP is more researched than EICP based on the number of publications by year.

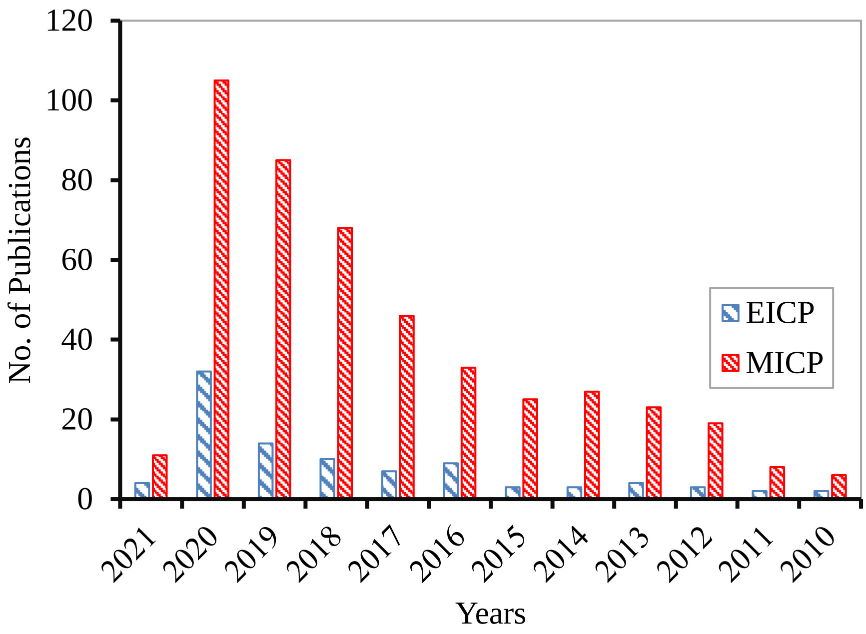

Figure 1.2 Increasing trend of the number of publications on MICP and EICP (2010 - February 2021)

1.2 Problem Statement

Earthquake-induced soil liquefaction is one of the most catastrophic geohazards and is a major source of concern as it threatens trillions of dollars' worth of infrastructure worldwide that is built on and in liquefiable soil deposits. Soil liquefaction can lead to massive soil displacement, settlement and the eventual collapse of infrastructures (Kramer, 1996). An example of the effects of soil liquefaction is the mass destruction of about 15,000 single-family houses when a moderate (magnitude 6.3) earthquake shook Christchurch, New Zealand (Rogers *et* *al.,* 2015). Although the conventional techniques such as preloading (to achieve rapid consolidation densification through compaction) and chemical grouting are usually employed to mitigate the effects of soil liquefaction, these techniques require high energy for execution and the used chemical admixtures may adversely affect the environment. Meanwhile, the production of additives such as cement and lime can lead to a high carbon footprint in the environment, where injecting these additives may contaminate the nearby soil and groundwater body (DeJong *et al*. 2010; Dejong *et al.*, 2006)

In the last decade, many studies have been conducted to assess the application of biocementation methods namely MICP and EICP to improve the strength and resistance to liquefaction of soils (Simatupang and Okamura, 2017; Xiao *et al.*, 2018). Meanwhile, the performance of biocementation depends on factors such as the pH, concentration of bacteria/urease, temperature and concentration of cementation reagent (CCR). However, the bone of contention still lies with the CCR; some studies have obtained the optimum performance of biocementation to occurs at higher CCR (≥1M) (Almajed, *et al.*, 2018; Carmona and Oliveira, 2017), while others reported otherwise (Okwadha and Li, 2010s; Soon *et al.*, 2013). Therefore, more studies need to be conducted on the effect of CCR on the precipitation of calcium carbonate prior to its application in soil improvement. Furthermore, despite the recent advances made in biocementation of soil, there are still environmental concerns regarding the fate of ammonium by-products produced. Methods to manage and reduce ammonium following biocementation will likely be needed as the technology transitions toward industrial field-scale application. Hence, this study explores the use of palm oil fuel ash (POFA) incorporated into the sand mixture to serve as ammonium absorbent. Another setback of biocementation is the non-uniform formation of calcium carbonate within the soil column, which is likely to affect the strength of the biocemented soil. Based on the studies conducted so far, the comparison between MICP and EICP has not been exhaustively carried out in terms of the amount and precipitation ratio of calcium carbonate formed. Therefore, it is important to adopt a treatment method that is likely to produce biocemented sample with uniform distribution of calcium carbonate. Likewise, the comparative performance of MICP and EICP be carried out to adopt the most efficient method for the soil treatment.

Malaysia is one of the highest producers of palm oil in the world, and this has led to the production of the high amount of palm oil fuel ash (POFA) as one of the by-products from the palm oil industries (Adebayo *et al.,* 2021; Mahmoud *et al.*, 2021). One way to minimize the exploitation of natural materials is to utilize the appropriate materials from the industry as by-products or waste materials. Such material is the palm oil fuel ash (POFA) which is usually dumped into an open field of a palm oil industry, causing environmental and health hazards. However, problems can be reduced by incorporating POFA into the soil system to increase strength and absorb the ammonium by-product produced from biocementation process.

1.3 Research Objectives

This study aims to evaluate the suitability of using bio-mediated soil improvement in the mitigating liquefiable sandy soil.

The following objectives were considered for the study.

i. To validate the bacteria strain through genomic identification and determine the effects of temperature, pH and salt on the growth profile.

ii. To determine the effect of the varying concentration of cementation reagent on the amount and efficiency of carbonate precipitation in MICP and EICP processes.

iii. To determine the effect of palm oil fuel ash (POFA) on the strength and ammonium reduction of EICP treated soil.

iv. To assess the effects of EICP treatment on the unconfined compressive strength liquefaction resistance of sandy soil.

1.4 Scope of the Study

Bio-mediated soil improvement research is an emerging field which utilises the knowledge of microbiological, geochemical and geotechnical engineering to improve the properties of various soils. This study focuses on the suitability of using biomediated soil improvement techniques to mitigate liquefaction in sandy soil. This laboratory-based research used the MICP and EICP techniques to achieve biocementation. The bacterial strain used in MICP was *B. megaterium.* Meanwhile, a plant-derived urease enzyme was used in EICP. The variables considered in this study include the concentrations of cementation reagent, curing temperature and period, number of the treatment cycle, percentages of POFA content, relative density, cyclic stress ratio (CSR) and confining pressure. The effectiveness of the treatment process was evaluated using UCS, cyclic resistance and formation of $CaCO_3$ within the soil matrix. Therefore, the experimental work in this study comprises of three main phases.

The first phase involves the culturing of bacteria, determining the effects of environmental factors (pH, temperature and salt content) on the growth of *B. megaterium* and test tube tests to determine the amount of $CaCO_3$. In the second phase, the effectiveness of EICP treatment on sandy soil was assessed through a series of UCS tests. While the third phase evaluates the effects of biocementation on the cyclic resistance of sandy soil through a series of cyclic triaxial tests. In this study, the evaluation of the soil's dynamic properties was carried out using the cyclic triaxial machine by subjecting it to a frequency of 1Hz to stimulate earthquake loading. This is because the biocementation technique for soil treatment is still in its infancy state. Therefore, it will require proper evaluation on small-scale samples before upscaling to larger samples. Furthermore, the mineralogical and microstructural analyses cut across all phases which include X-ray diffraction analysis (XRD), x-ray fluorescence (XRF), Scanning Electron Microscopy (SEM) and Energy Dispersion Spectroscopy (EDS).

1.5 Significance of the Study

More civil infrastructures are being erected to meet the overgrowing societal needs due to rapid population growth. However, a limitation for the construction of these infrastructures is the limited availability of good soil. For instance, in Malaysia, some developmental projects are constructed along shorelines or on reclaimed land in which the soil may liquefy upon significant movement (Hashim *et al.*, 2017; Marto *et al.*, 2014). Although Peninsular Malaysia is geographically free from seismic waves, recently it experienced low seismicity from a Sumatra active fault which is 350 km away (Marto *et al.*, 2013). Therefore, it is important to consider liquefaction mitigation related research in Peninsular Malaysia. This study will contribute in providing an environmentally friendly technique to mitigate the effects of liquefaction in sandy soil. Moreover, this study compares the performance of *B. megaterium* and plant-derived urease in $CaCO_3$ precipitation and biocementation of sandy soil. It also investigates the microstructural properties of biocemented soil towards its performance by analysing the pore spaces within the treated soil matrix. Furthermore, this study is expected to add to the existing literature on bio-mediated soil improvement and provide a baseline for the field application of the new technology.

1.6 Thesis Structure

This thesis is organised into seven chapters. Chapter one provides the background of the study, followed by the problem statement, the aims and objectives, scope and significance of the study and ends with the structure of the thesis.

Chapter two presents a review of relevant literature on the use of biocementation (MICP and EICP) in soil improvement and mitigation of liquefaction in soils. It also discusses the factors that affect the formation of $CaCO_3$ and strategies of soil treatment using MICP and EICP. The mechanism of soil liquefaction, factors that affect liquefaction and the conventional method to mitigate liquefaction in soil along with their drawbacks are also described in this chapter.

Chapter three presents in detail the materials and methods used in the study which includes a concise procedure to conducting the physical, geotechnical, chemical, mineralogical and microstructural tests on the soil. Chapter four discusses the results of the genomic identification of the bacteria and the effects of environmental factors on bacterial growth. The chapter also presents the optimisation and mineralogical confirmation of $CaCO_3$ precipitates through test-tube tests of both MICP and EICP.

Chapter five describes the physical properties and strength of biocemented sandy soil via EICP. The effects of the number of treatment cycles, curing temperature, relative density and concentrations of cementation reagent on biocemented soil were also presented in this chapter. Furthermore, the relationship between UCS and $CaCO_3$ content and microstructural analysis. Chapter six presents the findings on liquefaction resistance of biocemented soil. The effects of the CSR, relative density and confining pressure pore water pressure build-up is presented. Finally, Chapter seven summarises the findings, concludes the research and provides recommendations for future studies.

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LIST OF PUBLICATIONS

Journal Articles

1. **Muhammed, A. S.,** Kassim, K. A., Ahmad, K., & Zango, M. U. Makinda J. (2021) Influence of Multiple Treatment Cycles on the Strength and Microstructure of Biocemented Sandy Soil. International Journal of Environmental Science and Technology **(ISI Indexed)**

2. **Muhammed, A. S.,** Kassim, K. A., Zango, M. U., C. S. Chong, Ahmad, K. & Makinda J. Bio-cementation of Sandy Soil at different Relative Density International Journal on Emerging Technologies 11(4): 486-489(2020) **(Scopus Indexed).**

3. **Muhammed, A. S.,** Kassim, K. A., Zango, M. U., C. S. Chong, Ahmad, K. & Makinda J. (2020). A review on the use of biocementation technique in the mitigation of liquefaction in sandy soil. *GEODERMA* (Under Review) **(ISI Indexed).**

4. **Muhammed, A. S**., Kassim, K. A., Zango, M. U., C. S. Chong, Ahmad, K. & Makinda J. (2021). Enhancing the of Strength of Sandy Soil through Enzyme-Induced Calcite Precipitation. *International Journal of Geosynthetics and Ground Engineering*. (Under Review) **(Scopus Indexed).**

Conference Proceedings

1. **Muhammed, A. S.,** Kassim, K. A., & Zango, M. U. (2018). Review on biological process of soil improvement in the mitigation of liquefaction in sandy soil. *The 12th International Civil Engineering Post Graduate Conference (SEPKA) The 3rd International Symposium on Expertise of Engineering*

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2. **Muhammed, A. S.,** Zango, M. U., Kassim, K. A., Ahmad, K., & Umar, M. (2019, May). Effects of cementation reagent on the precipitation of calcium carbonate induced by Bacillus Megaterium. *11th International Conference on Geotechnical Engineering in Tropical Regions (11th GEOTROPIKA) and 1st International Conference on Highway and Transportation Engineering (1st ICHITRA).* In IOP Conference Series: Materials Science and Engineering (Vol. 527, No. 1, p. 012022). IOP Publishing. **(Scopus Indexed).**

3. **Muhammed, A. S.,** Kassim, K. A., Zango, M. U., C. S. Chong, Ahmad, K. & Makinda J. (2020). Effect of Palm oil Fuel Ash on the strength and ammonium by -product removal of biocemented sandy soil. *The 13th International UNIMAS Engineering Conference 2020 (EnCon 2020). (Accepted) – **BEST PAPER AWARD***