Geo-environmental and Liquefaction Potential Assessment on Poorly Graded Sandy Soil Improved by Bamboo Materials

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SITO ISMANTI

August, 2017

GEO-ENVIRONMENTAL AND LIQUEFACTION POTENTIAL ASSESSMENT ON POORLY GRADED SANDY SOIL IMPROVED BY BAMBOO MATERIALS

A DISSERTATION

Submitted to
Kyushu University
in partial fulfillment of the requirements
for the degree of
Doctor of Engineering

by

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CERTIFICATE

The undersigned hereby certify that they have read and recommended to the Graduate School of Engineering for the acceptance of this thesis entitled, “***Geo-Environmental and Liquefaction Potential Assessment on Poorly Graded Sandy Soil Improved by Bamboo Materials***” by **Sito Ismanti** in partial fulfillment of the requirements for the degree of **Doctor of Engineering**.

Dated: August, 2017

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ABSTRACT

Poorly graded sandy soil is a soil type with high potential of liquefaction. Liquefaction is defined as the phenomenon of the strength loss of saturated and cohesionless soils due to the increasing pore water pressure under dynamic loading. Increasing liquefaction resistance can be achieved by mixing method using stabilizer material such as cement that is widely used and applied in field. The utilization of cement is the last alternative since other methods are more costly. However, soil improvement by cement is still considered as an expensive material, especially in developing countries. In addition, to the environmental point of view, cement production is an important concern. Based on Synthesis Report of Climate Change 2014 by Intergovernmental Panel on Climate Change (IPCC), cement production contributes 34.8GtCO_2/year annual CO_2 emission together with fossil fuel combustion and flaring. Since 1970, these activities have tripled. Therefore, cement replacement materials were studied by researchers. Concerning the environmental issue, utilization of natural material as the environmental-friendly and high sustainability material was considered to be studied.

Bamboo is a kind of natural resource that has ability to grow in various conditions, especially in tropical and sub-tropical countries. By its abundance, bamboo has high potential to be utilized in geotechnical application. In the previous study, bamboo chips and bamboo flakes were reliable in improvement of soft ground, erosion resistance, and high water content of excavated mud. In addition, bamboo leaf ash (BLAsh) which has high pozzolanic content was investigated to replace cement in high plasticity soil improvement. However, the combination among bamboo flakes, bamboo chips, and BLAsh in cemented poorly graded sandy soil under saturated condition has not been investigated yet. In this study, analysis based on the experimental study was conducted on aiming at (1) investigation of bamboo material effect in improvement of liquefaction resistance, (2) investigation of the environmental impact by this proposed method,

and (3) recommendation of application system in field. The brief discussion of this study is presented into seven chapters as follows:

In Chapter 1, environmental problem of cement production and mechanical problem of poorly graded sandy soil as the research background were introduced. The availability of bamboo potential and its advantages as a high sustainable material were reviewed as the motivation to solve the problem. Research objectives, limitations, contributions, and outline structure of this study were also explained.

In Chapter 2, utilization of bamboo flakes and bamboo chips in geotechnical field was reviewed. In order to determine the optimum type between bamboo flakes and bamboo chips, water absorbability test apparatus was developed. In the constant volume of bamboo flakes and bamboo chips, relationship between water absorbability and elapsed time was determined using this simple test apparatus. In addition, physical characteristic, mechanical properties, and microscopic analysis of bamboo material addition in cemented sandy soil improvement were examined by elongation-flatness ratio, static triaxial test, and Scanning Electron Microscopic (SEM) test, respectively. It was found that cutting machine produces intact structure of bamboo chips, whereas rubbing machine produces fiber structure of bamboo flakes. The form of structure affects the water absorbability and mechanical properties of bamboo material in cemented sandy soil. Based on the comparison, intact form of bamboo chips provides higher performance compared to bamboo flakes by the consistent water absorbability and the higher shear strength in cemented sandy soil mixture.

In Chapter 3, investigation of bamboo chips effect to the permeability and dilative behavior of cemented sandy soil was highlighted. The negative tendency to the permeability and dilative behavior was shown by bamboo chips-sandy soil mixture compared to cemented sandy soil. Conversely, the addition of bamboo chips in cemented sandy soil provides positive tendency. It can be concluded that bamboo chips is reliable as the reinforcement material in cemented sandy soil instead of cement replacement. Furthermore, 6 mm bamboo chips provided optimum result on the improvement of permeability and dilative behavior compared to 10 mm bamboo chips.

In Chapter 4, effect of BLAsh utilization in cemented bamboo chips-sandy soil mixture was investigated. Investigations to determine chemical compound, mechanical properties, liquefaction resistance, and impact to the environment were conducted by Energy Dispersive X-Ray (EDX) test, static triaxial test, cyclic triaxial test, and measurement of pH value and heavy metal content, respectively. Content of BLAsh was evaluated in the constant total amount of cement and BLAsh content in the mixture. Based on the relationship among content of CaO, SiO_2, and the difference of maximum deviator stress (q_{max}) of mixture, it was concluded that BLAsh is able to replace cement totally. It was shown by same strength of totally cement replacement by BLAsh with the cemented bamboo chips-sandy soil mixture (without BLAsh). However, small amount of cement provided higher strength because CaO content in cement generates more $Ca(OH)_2$ as the result of cementation reaction and as the reactant in secondary pozzolanic reaction by BLAsh at once. Static and cylic triaxial test provide consistent result of the optimum amount of BLAsh. 75% of BLAsh content in replacing cement was the optimum mixture design in improving qmax and liquefaction resistance. In addition, positive effect of BLAsh addition to the environment was also presented by the decreasing pH value and heavy metal content.

In Chapter 5, application of proposed mixture in factual problem in field, i.e. liquefaction occurrence after Yogyakarta Earthquake, Indonesia, on May 2006 was presented using Japan approach of liquefaction potential analysis. The assessment requires blow-count of Standard Penetration Test (N_{SPT}) value as the practical parameter in field. This chapter proposed the assessment by converting the result of undrained triaxial test as undrained shear strength (S_u) to N_{SPT} value following the empirical equation suggested by reference. The proposed mixture applied in this assessment is the optimum mixture found in the previous chapter, i.e. 75% cement replacement by BLAsh. Based on the result, decreasing liquefaction potential was shown significantly by the proposed mixture.

In Chapter 6, life cycle assessment (LCA) of BLAsh utilization in liquefiable soil improvement was conducted. In addition, application system of bamboo material utilization was generated. Based on the system, reducing bamboo leaf waste was calculated, equation to calculate total cost of system was proposed, and life cycle CO_2 ($LCCO_2$) of BLAsh production was presented. By $LCCO_2$, high CO_2 emission was shown in BLAsh production. However, the high carbon sequestration of bamboo trees was proposed to solve this problem. Regarding the concern to maintain the sustainability of bamboo forest itself, bamboo selection and harvesting time management were recommended in applying this method in field.

In Chapter 7, conclusions of each chapter and recommendations for future works were presented.

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NOMENCLATURE AND ABBREVIATIONS

a	Maximum acceleration at the ground surface or peak ground acceleration, gals
AAS	Atomic Absorption Spectrometer
AASHTO	American Association of State Highway and Transportation Officials
Al_2O_3	Alumina
ASTM	American Society for Material Testing
B	Project effect
BLAsh	Bamboo Leaf Ash
CaO	Calcium oxide
$Ca(OH)_2$	Calcium hydroxide
CaO/SiO_2	Ratio between calcium oxide and silica
CASH	Calcium aluminate silicate hydrate gel
CBR	California Bearing Ratio
CKD	Cement Kiln Dust
Class C pozzolan	pozzolanic and cementitious fly ash from burning lignite or bituminous coal
Class F pozzolan	fly ash from burning anthracite or bituminous coal
Class N pozzolan	raw or calcined natural pozzolan
CO_2	Carbon dioxide
CSH	Calcium silicate hydrates
CSR	Cyclic Stress Ratio
c_u	Undrained cohesion, kPa
C	Direct cost
C_C	Construction cost
Cd	Cadmium

CF_i	Total carbon content
C_I	Initial cost
C_K	Storing cost
C_S	Processing cost
Cr	Chromium
C_T	Transportation cost
Cu	Copper
C_w	Coefficient reflecting characteristics of earthquake/seismic motion
C_1 and C_2	Coefficient based on finer content
$\overline{CU}$	Consolidated and undrained method of triaxial test with pore water pressure measurement
DA	Double Amplitude
D_{50}	Average or mean particle sizes, mm
D_{max}	Maximum grain size, mm
D_r	Relative density
E	Environmental cost
E_0	Environmental cost during the manufacturing process
E_C	Environmental cost by impact to ecosystem
E_T	Environmental cost consumed by transportation
EDX	Energy Dispersive X-ray
EKB	Essential Knowledge Briefings
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
F	Coefficient based on liquefaction possibility
F_c	Finer content, %
FCF_i	Fraction of fossil carbon in total carbon
Fe	Iron

Fe_2O_3	Ferric oxide
F_L	Liquefaction possibility
g	Acceleration of gravity (980 gals)
$GtCO_2$/year	Gigatonnes of carbon dioxide per year
G_s	Specific gravity
GWL	Groundwater level, m
H_2O	Water
I_p	Plasticity index
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JGS	Japanese Geotechnical Society
U_c	Coefficient of uniformity
UCS	Unconfined Compressive Strength
K_2O	Potassium oxide
L	Seismic shear stress ratio
LCA	Life Cycle Assessment
$LCCO_2$	Life Cycle of Carbon Dioxide
Mg	Magnesium
MgO	Magnesium oxide
M_w	Moment magnitude
M_1	Dry mass of improved sandy soil
M_2	Mass of bamboo chips/bamboo culm
M_3	Mass of bamboo leaf ash
M_4	Dry mass of bamboo leaf
M_5	Mass of bamboo leaf by cultivated bamboo tree
N	Number of cycles
Na_2O	Sodium oxide

ND	Not determined
N_{SPT} or N	N-value acquired from Standard Penetration Test
N_a	Amended N-value based on the grains size
NP	Non plastic soil
N_1	Normalized N-value for effective stress of 1 kgf/cm^2
OF_i	Oxidation factor
OPC or PC	Ordinary Portland Cement
p’	Effective mean principal stress, kPa
P_2O_5	Phosphorus pentoxide
Pb	Lead
pH	A numeric scale used to specify the acidity or basicity of an aqueous solution
P_L	Liquefaction potential
PT line	Phase transformation line
q	Deviator stress, kPa
$q_{at15\%}$	Deviator stress at 15% of strain, kPa
q_{max}	Maximum deviator stress, kPa
Δq_{max}	Difference of maximum deviator stress between mixture with and without bamboo leaf ash, kPa
q_{max0}	Maximum deviator stress of mixture without bamboo leaf ash, kPa
q_{maxi}	Maximum deviator stress of mixture with bamboo leaf ash, kPa
q_u	Unconfined compressive strength, kPa
r	Average of ratio between bamboo leaf and bamboo culm
R	Dynamic shear strength ratio
r_d	Reduction factor for dynamic shear stress (= 1.0 – 0.015z)
R_L	Undrained cyclic shear resistance

S	Unit price of disposal activity
SEM	Scanning Electron Microscope
SiO_2	Silica
SO_3	Sulfur trioxide
SPT	Standard Penetration Test
SS-550	Super Scan-550 apparatus
S_u	Undrained shear strength, kPa
SW x dm	Total dry weight of waste
T	Total cost
TiO_2	Titanium oxide
W	Volume of residual waste
w_{sat}	Natural moisture content in a saturated state, %
W(z)	Weight function of the soil depth (= 10 – 0.5z)
XRF	X-Ray Fluorescence
z	Depth from the soil surface, m
Zn	Zinc
σ	Principal stress, kPa
σ_d	Cyclic shear stress
σ_v	Total stress of soil, kgf/cm^2
σ'_v	Effective stress of soil, kgf/cm^2
σ_1	Maximum principal stress, kPa
σ'_1	Effective maximum principal stress, kPa
σ_3	Minimum principal stress or confining pressure, kPa
σ'_3	Effective minimum principal stress, kPa
Δu	Pore water pressure, kPa
$\Delta u/\sigma'_0$	Excess pore water pressure ratio
ΔH	Difference height, mm

ε_a	Axial strain, %
α	Coefficient to calculate undrained shear strength based on type of N-value
φ	Internal friction angle, ^{o}
φ_d	Internal friction angle in drained condition, ^{o}
γ_d	Dry unit weight, kN/m^3
γ_{sat}	Saturated unit weight, kN/m^3
ρ_s	Solid density, g/cm^3
τ	Shear stress, kPa
\$/kg-CO_2	US dollar for 1 kg of CO_2

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Mixing method by stabilizer material into soil is widely applied method to improve the properties. Cement is the stabilizer agent widely used and applicable to the various types of soil. It is because the performance of cement does not depend on the type of minerals in the soil, but due to the reaction between cement and water. This reaction provides bonding, hardening and strengthening in soil stabilization (Ates, 2016).

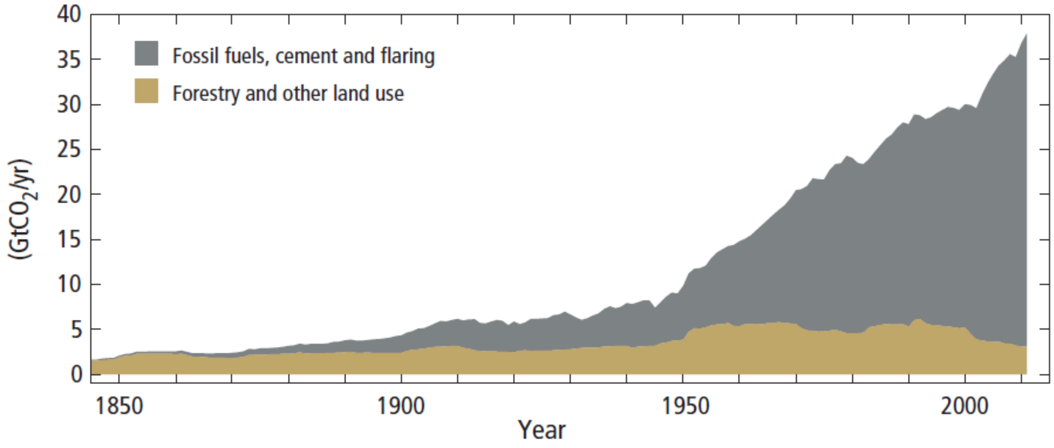

Figure 1.1. Global anthropogenic CO_2 emissions.

In the environmental aspect, cement production is an important concern. Based on Synthesis Report of Climate Change 2014 by Intergovernmental Panel on Climate Change (IPCC), cement production contributes 34.8GtCO_2/year annual CO_2 emission together with fossil fuel combustion and flaring. Since 1970, these activities have tripled (Fig. 1.1). Therefore, there are some studies proposing substitution materials to reduce cement utilization, including the addition of high pozzolanic materials or reinforcement in the cemented sandy soil such as fly ash, nanosilica, zeolite, glass fiber (Choobbasti et al., 2015; Mola-Abasi and Shooshpasha, 2016; Ates, 2016). Nowadays, the investigations also began to focus on the sustainability. Thus, natural materials become the main concern in this effort.

1.1.1 Problem of poorly graded sandy soil

Liquefaction is defined as the phenomenon of the strength loss of saturated and cohesionless soils due to the increasing pore water pressure under dynamic loading. Some conditions must be fulfilled for occurring liquefaction, i.e. the soil must be submerged below the water table, the soil is the loose/soft to moderately dense/stiff, the ground shaking is intense, and the duration of ground shaking is sufficient for the soils to lose the shear strength (Kumar, et al, 2012). On the gently sloping to flat soil surface, liquefaction may lead to ground oscillation or lateral spread as the result of flow deformation. Moreover, other types of liquefaction damage are reconsolidation as the result of compacting phenomenon of loose soil and sand boiling as the result of dissipating excess pore water pressure (Youd and Idriss, 2001).

As one of the similarities of natural conditions between Japan and Indonesia, these both countries are located on the boundary of active tectonic plate. This active tectonic plate forms the volcanic arcs and oceanic trenches partly encircling the Pacific Basin called as Ring of Fire (Lindeberg, 2001) shown in Fig. 1.2. This condition causes these countries have high potential in receiving earthquake. Therefore, the phenomenon of liquefaction also becomes vulnerable. Figure 1.3 focuses on the earthquake potential in Indonesia, especially in Java Island. There are many points of earthquake occurrence shown by black small circles.

Liquefaction phenomenon was occurred in several sites in Yogyakarta City in Java Island, Indonesia after Mid Java Earthquake on May 27, 2006. Japanese Geotechnical Society (JGS) survey team (Koseki et al., 2007) investigated on the geotechnical issues. Figure 1.3(b) shows the location of the earthquake. In addition, Fig. 1.4 shows the damages and liquefaction phenomenon due to this earthquake. Selection of soil type in this research is based on this investigation result by Koseki et.al. (2007). There are compatibility properties of Toyoura sand with liquefied soil in several sites. Figure 1.5 shows that the grain size distribution curve of Toyoura sand is located among the other curves.

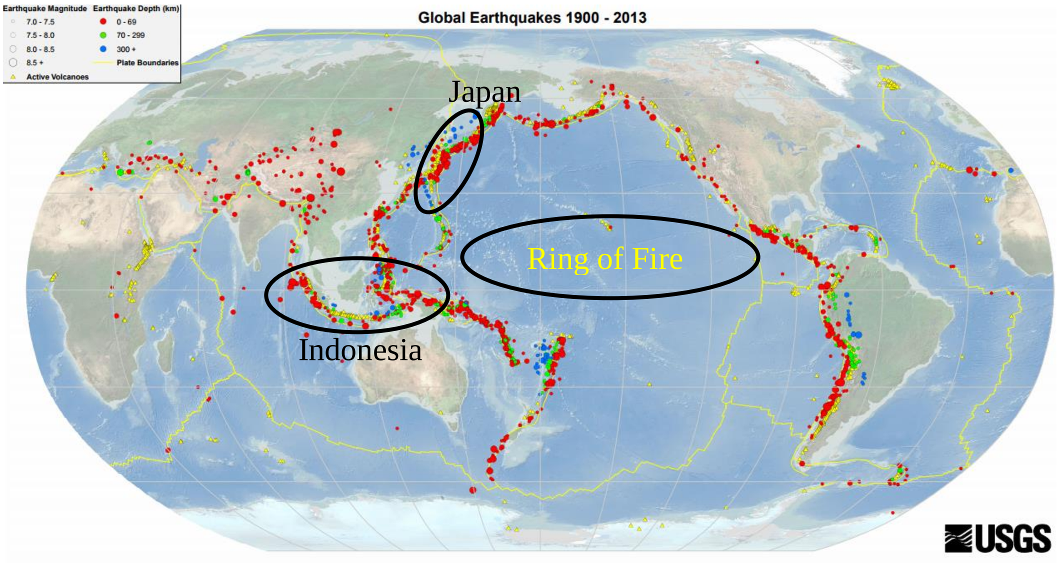

Figure 1.2. Map of Ring of Fire and location of Japan and Indonesia. (Modified after https://earthquake.usgs.gov/earthquakes/byregion/)

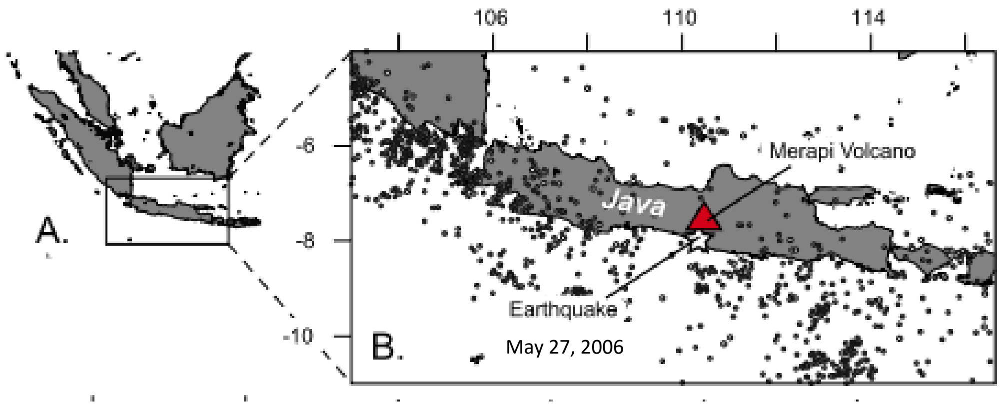

Figure 1.3. Map of (a) West part of Indonesia and (b) earthquake area on Java Island, Indonesia. Historical earthquake data is shown by small black circles, whereas star sign shows the location of Yogyakarta Earthquake on May 26, 2006. (Modified after Walter et al., 2008)

Based on this reason, Toyoura sand was utilized in all experimental activities in this study. The index properties of Toyoura sand are G_s = 2.64, D_{50} = 0.17 mm, U_c = 1.75, e_{max} = 0.953, e_{min} = 1.352. Relative density (D_r) of 35% was consistently used in all mixture variations here.

(a) (b)

(c) (d)

Figure 1.4. (a), (b) Damages due to Yogyakarta Earthquake May 26, 2006, (c) inclined floor and (d) lateral spreading due to liquefaction phenomenon. (Rosyidi et.al., 2008)

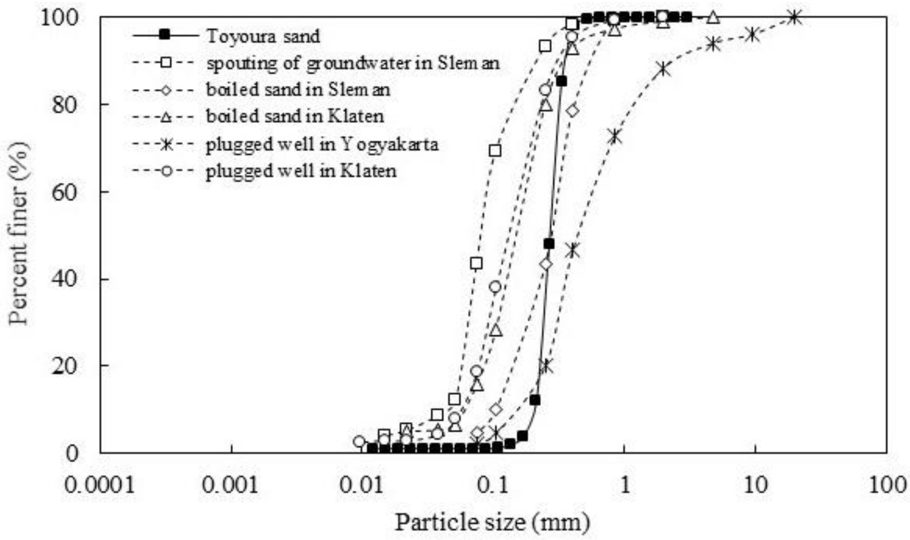

Figure 1.5. Particle size distribution curve of the liquefied soil in several sites in Indonesia. (Modified after Koseki et al., 2007).

To modify and improve the poorly graded sandy soil, generally, utilization of cement in soil improvement is the final selection since others are more costly. However, soil improvement by cement is still considered as a quite expensive alternative material, especially in some developing countries. New material and method are highly required to reduce and replace cement utilization in soil improvement. High sustainability, high potential in economic and social approach, and by all means, satisfying the technical requirement are important consideration in determining the proposed idea.

1.1.2 Bamboo and its potential

Bamboo is classified as a specialized group in the Grass family (Wong, 2004). Bamboo is an ancient woody grass and included as a major non-wood forest product (Lobovikov et al., 2007). Following three major regions, the Asian-Pacific Region, the Americas Region, and the African Region, Yuming and Chaomao (2010) provided the sketch map to depict the distribution of bamboo worldwide. Figure 1.6 shows the bamboo growth is concentrated in the belt of equator or in tropical and sub-tropical countries.

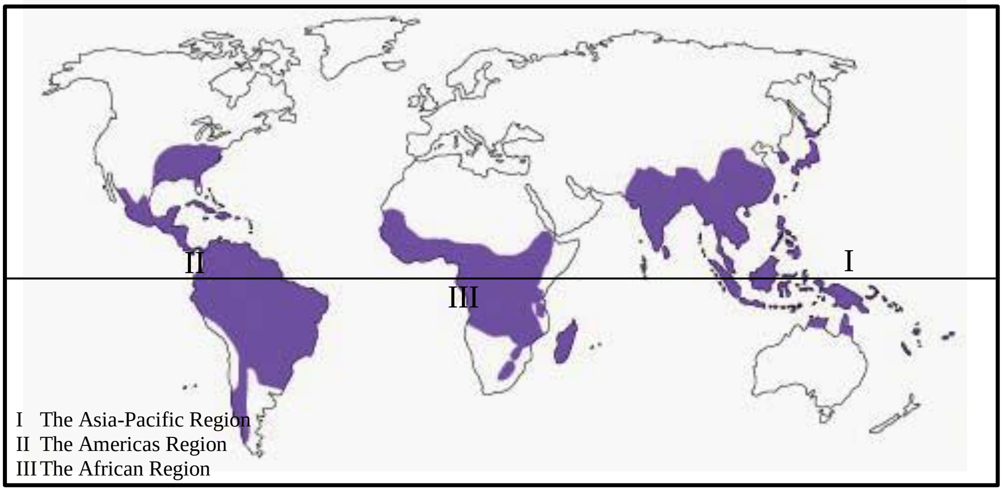

Figure 1.6. Sketch map of world bamboo distribution.
(Yuming and Chaomao, 2010)

Lobovikov et al. (2007) reported the distribution of bamboo resources by continent in 2005. Asia has the richest bamboo resources by its 65 percent of total world bamboo resources shown in Fig. 1.7. This report also showed the extent of bamboo forest in Asia, Africa, and America. Bamboo forest has 3.2 percent of proportion to the total forest area. In Asia, India is the major country with the largest bamboo forest area (almost 11.4 million hectares), followed by China and Indonesia with over 5.4 million and 2 million hectares of bamboo forest area, respectively. Figure 1.8 is the photographs of part of bamboo forest in Yogyakarta, Indonesia. Japan is in the 8th position to the 16 countries listed in the report. By its total forest area (about 25 million hectares), bamboo forest area in Japan has 0.6 percent of proportion. This data shows that the availability of abundant bamboo is a high potential to be utilized in various applications. The report also concluded bamboo product statistics, i.e. raw materials, charcoal, housing, pulp, paper, cloth, panels, flooring, weaving products, crafts, fuel, shoots, furniture, culture, protects steep slopes, soils and water ways, prevents soil erosion, provides carbon sequestration, and many other ecosystem benefits.

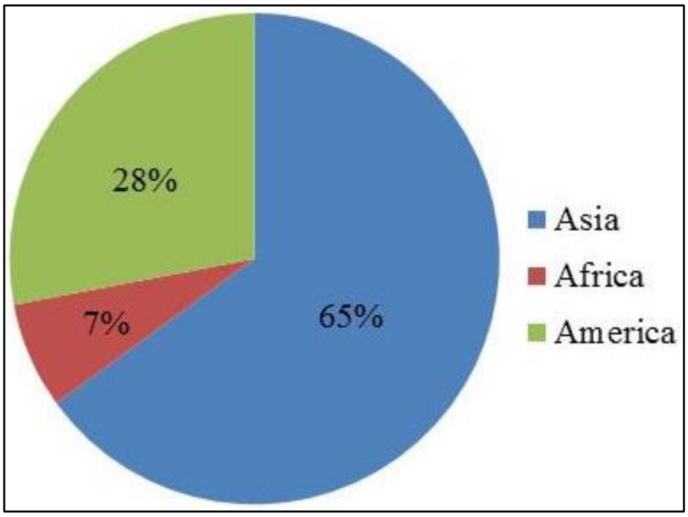

Figure 1.7. Distribution of world bamboo resources by continent.

(Lobovikov et al., 2007)

Figure 1.8. Bamboo forest in Yogyakarta, Indonesia.

1.1.3 Part and utilization of bamboo material

Bamboo species are divided into two categories based on the structure of root, i.e. clumping and running (Brenner, 2008). Bamboo tree has four main parts such as leaf, branches, culm/stem, and root. The utilization of bamboo parts is summarized in Figure 1.10. Almost all parts of the bamboo tree can be utilized. There are still many applications using bamboo materials which have not been shown in the figure. Starting from process using simple to modern equipment, bamboo can be turned into useful products in some applications. Its abundance, strength, and durability are the main reason why bamboo is able to substitute wood material and some other applications.

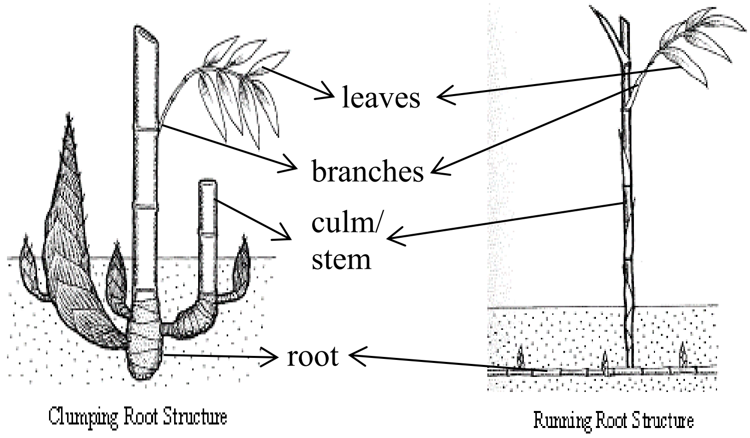

Figure 1.9. Parts of bamboo trees. (Modified after http://bamboosourcery.com/)

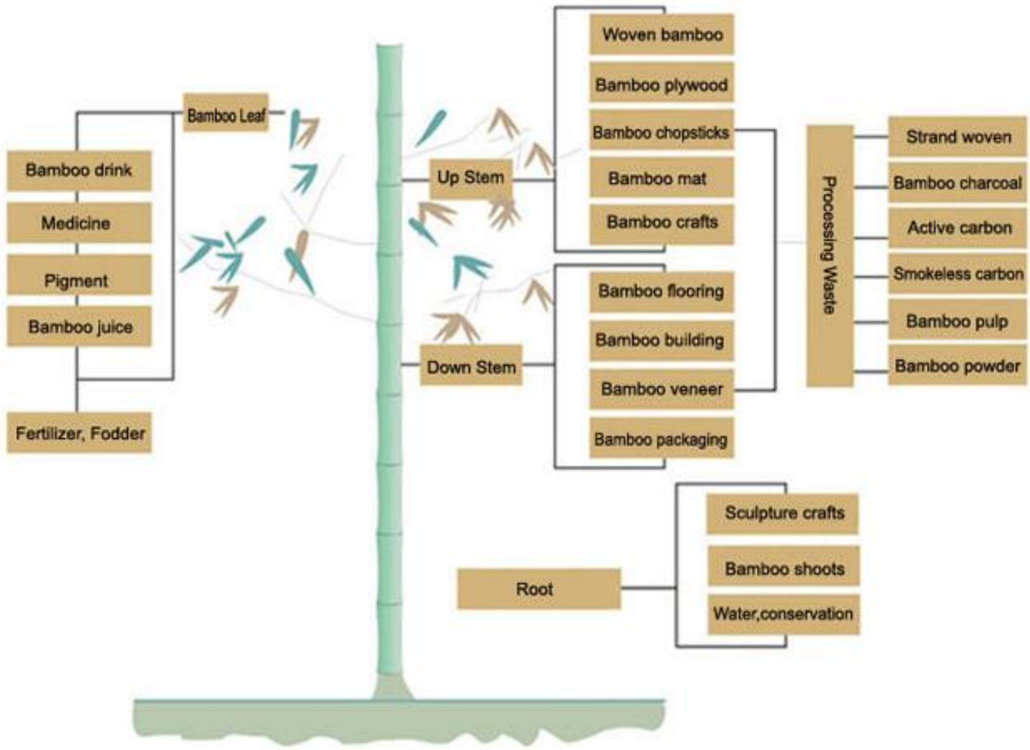

Figure 1.10. Utilization of bamboo based on the part of bamboo.
(Source: http://bambooindustry.com/blog/bamboo-utilization/)

Based on the explanations above, bamboo as the abundant resources with its high sustainability and high technical properties is able to be chosen as a high potential material to solve the problem of poorly graded sandy soil.

1.2 Research objectives

The following are the objectives of this research expected to be achieved by each chapter:

1. to evaluate the affecting factors in utilization of bamboo culm and determine optimum type between bamboo flakes and bamboo chips,
2. to investigate effect of bamboo chips addition on dilative behavior and coefficient of permeability,
3. to investigate effect of bamboo leaf ash addition in cemented bamboo chips-sandy soil mixture comprehensively,
4. to investigate the improvement by proposed mixture in liquefaction potential assessment, and
5. to evaluate impact of the system to the environment by life cycle assessment.

1.3 Boundary condition

This research focused on the experimental activity to analyze the effectiveness of bamboo material in poorly graded sandy soil in short term period. The longest curing time conducted in this study is 14 days. The determination of curing time duration is based on the purpose of this study, i.e. to understand the trends of the effects provided by the bamboo material utilization as the new material in geotechnical point of view. In addition, bamboo material used in this research was obtained from bamboo forest in Itoshima, Japan.

1.4 Contribution of research and novelty

As the abundant material, especially in tropical and subtropical countries, bamboo utilization in geotechnical field has been widely applied. However, bamboo culm in the form of bamboo flakes and bamboo chips, and also bamboo leaf in the form of bamboo leaf ash (BLAsh) in the poorly graded sandy soil is the new method in geotechnical field. The following are main contributions and novelty in relation to achieving the research objectives:

1. Developed new application of bamboo utilization in improvement of liquefaction resistance.
2. Developed water absorbability test apparatus of bamboo flakes and bamboo chips.
3. Proposed type and size of bamboo material in improving cemented sandy soil.
4. Proposed optimum content of bamboo leaf ash (BLAsh) in replacing cement.
5. Recommended application system of BLAsh utilization in field.

1.5 Dissertation Outline

The structure of this research is shown in Fig. 1.11. This research contains 7 chapters that can be outlined as follows:

Chapter 1 describes general introduction of this research. It contains problem as the background, objective as the goal, boundary condition as the limitation, and the structure as the full image of this research.

Chapter 2 compares between bamboo flakes and bamboo chips characteristics. This chapter states the parameters that affect the characteristic in the mixture contains poorly graded sandy soil, cement, and water. In addition, the optimum type of bamboo material was concluded that would be utilized in the next chapters.

Chapter 3 focuses on the comparison between 6 mm and 10 mm bamboo chips in cemented sandy soil. This chapter investigates the effect of size and amount of bamboo chips in permeability and dilative behavior as the indicator of static liquefaction resistance. The optimum size and amount of bamboo chips is concluded to be used in the next chapters.

Chapter 4 investigates the effect of cement replacement by BLAsh in view point of chemical compound by EDX test and mechanical properties by static triaxial result. In addition, as the purpose of the utilization of bamboo material in poorly graded sandy soil, i.e. to increase the liquefaction resistance, result of cyclic triaxial test was presented. Furthermore, impact of the mixture in environment is shown in the end of the chapter.

Chapter 5 performs assessment of liquefaction potential factual problem in field based on the liquefaction occurrence in Yogyakarta, Indonesia using proposed material design.

Chapter 6 discusses about socio-environmental aspect of bamboo material, especially BLAsh material, utilization in partially cement replacement. Proposed system and suggestion in applying this method in field were presented to reach the optimum improvement in both technical and environmental points of view.

Chapter 7 concludes all result of investigations and analysis in this research. Based on these conclusions, future works were recommended.

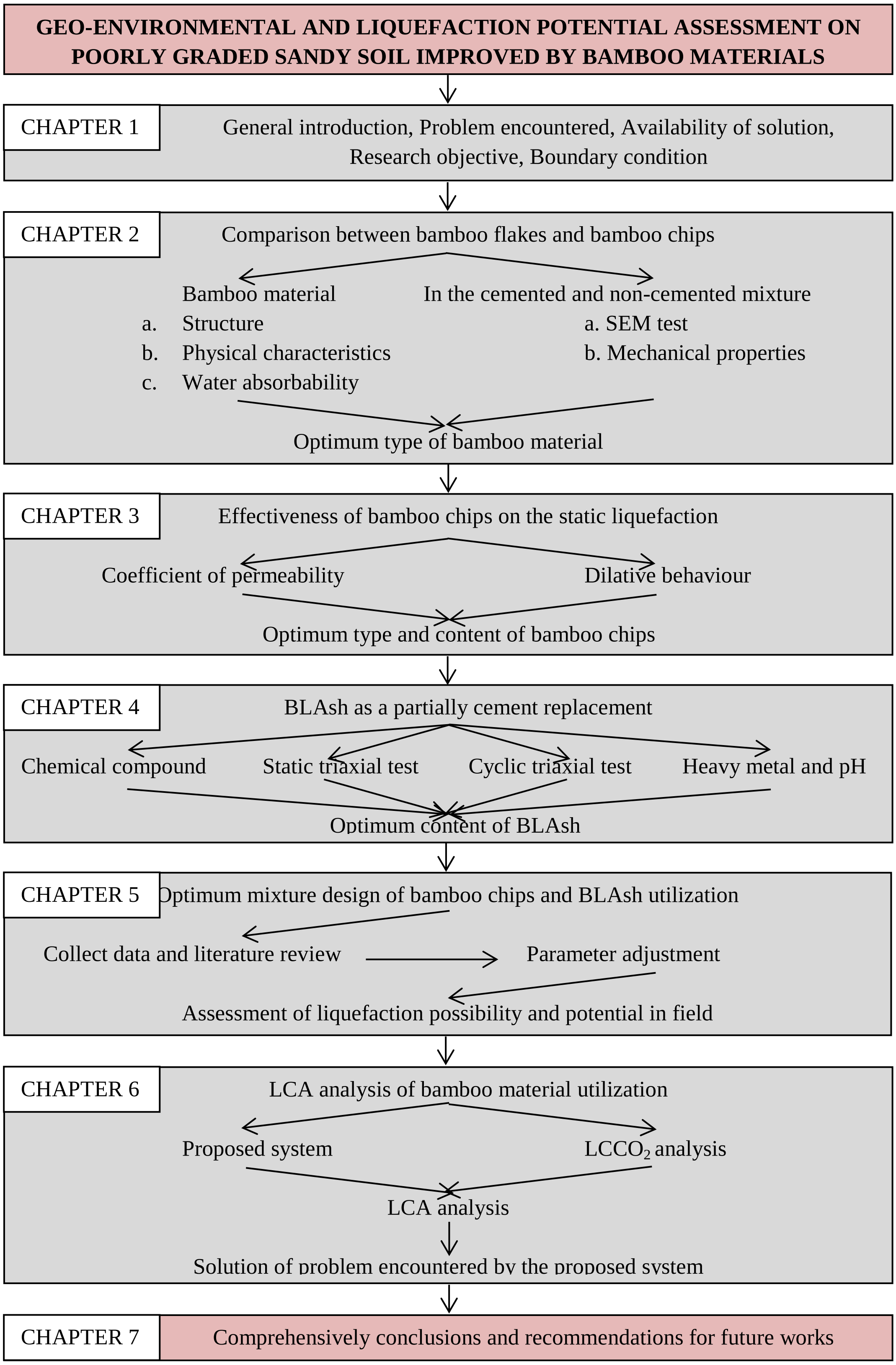

Figure 1.11. Research flow chart.

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CHAPTER 2

EVALUATION OF BAMBOO FLAKES AND CHIPS STRUCTURE ON CEMENTED SANDY SOIL IMPROVEMENT

2.1 Introduction

In this chapter, evaluation of bamboo flakes and bamboo chips in the sandy soil improvement is presented by experimental study. Utilization of natural material in soil improvement is reviewed. In addition, focusing on the bamboo material utilization, microstructure of bamboo culm is explained based on the references. The microstructure of bamboo culm is expected provide significant effect to the performance of bamboo flakes and bamboo chips in soil improvement. As the main properties of bamboo utilization in this application, water absorbability studies conducted by previous researchers are also summarized. To deepen the motivation of this evaluation, utilization of bamboo flakes and bamboo chips in other applications is also reviewed. Properties and effect of bamboo flakes and bamboo chips utilization in cemented sandy soil improvement were investigated.

2.2 Literature review

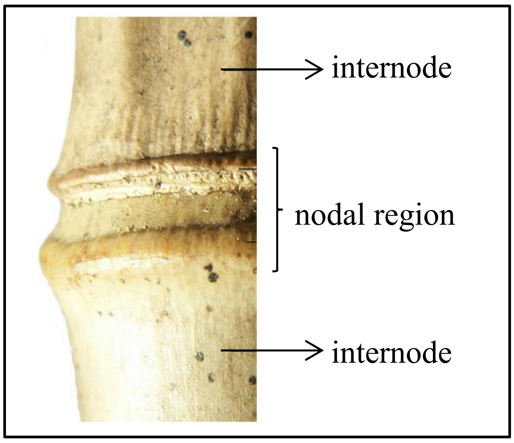
2.2.1 Natural material as an additive material in soil improvement

In the form of fiber, Hejazi et al. (2012) reviewed the utilization of natural and synthetic material in soil reinforcement. Due to its abundance, economic reason, and consideration to the environmentally friendly aspect, natural materials have been used in many developing countries in geotechnical applications. Improvement of the shear strength, compressibility, density, and hydraulic conductivity are the objective of the soil reinforcement by natural fibers. This concept has already known in ancient times. However, this method is still improved by some researchers to provide optimum result. Some kinds of natural materials that are widely used are coconut (coir), sisal, palm, jute, flax, barely straw, bamboo, and cane. Focus on bamboo fiber, Devi and Jempen (2016) investigated utilization of bamboo fiber in poorly graded sandy soil. Improvement was shown by increasing shear strength on the randomly distributed bamboo fiber-soil mixture using direct shear test. However, there was lack information about the causing factor of the improvement.

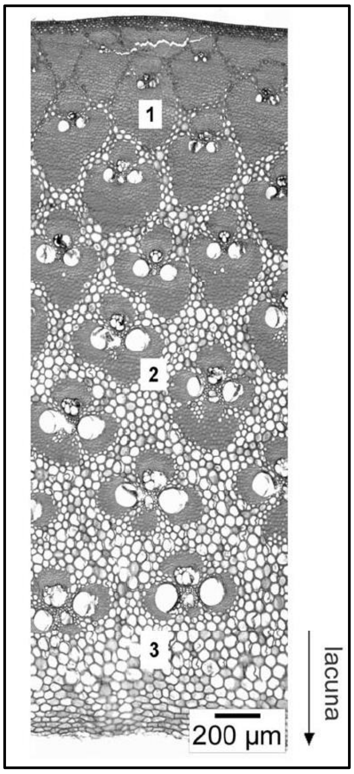
Tremblay et al. (2002) investigated the influence of organic materials addition in the cemented mixture. Generally, some organic compounds may delay or even inhibit the hydration process of cement. However, organic matter which is in the form of cellulose fibers does not cause important problems in the cementing process. This type of organic matter increases the plasticity and decreases the brittleness of mixture (Soroushian et al., 1995). This information supports this study to conduct the investigation regarding utilization of bamboo flakes and bamboo chips as the form of cellulose fibers in the cemented poorly graded sandy soil.

2.2.2 Structure of bamboo culm

Bamboo consists of roots, culm, and leaves. Part of bamboo that is processed into bamboo materials in this study is bamboo culm. Furthermore, this part of bamboo is processed to produce bamboo flakes and bamboo chips using rubbing and cutting machine, respectively. Bamboo culm consists of nodes and internode (Fig. 2.1(a)). Based on Liese (2003), Liese (2004), and Lybeer (2005), as a dominant part of bamboo culm, internode is divided into three main sections, including outer, middle, and inner parts indicated by the number 1, 2, and 3, respectively, in Fig. 2.1(b). Outer part consists of cortex which is densely packed cells, often cutinized and with wax coating. This section keeps the moisture and bamboo culm to spoil due to water. These properties causes the outer part of bamboo culm has hydrophobic properties. Middle part of bamboo culm consists of 50% parenchyma, 40% fibers, and vascular bundles. Fibers have good technical properties for providing strength of bamboo culm structure.



(a)



(b)

Figure 2.1. (a) Parts of bamboo culm and (b) structure of bamboo culm (Lybeer, 2005).

Liese (2003) and Liese (2004) also mentioned that besides its structure, chemical constituent in bamboo culm also has influence on the performance of bamboo materials in mixture. The dominant content is cellulose. This substance has a tendency to absorb water (hydrophilic). Other chemical constituents are hemicelluloses, lignin which has the properties to maintain rigidity of bamboo culm, silica, and starch as the most important part of the plant as fortifying component. Silica has a capable of maintaining a material to against degradation, but in the bamboo culm, its small amount has no impact against biodegradation. Regarding the pH value of bamboo, Junior et al. (2009) stated that the pH distribution of bamboo ranged from 5.5 to 6.8. This value may affect the hydration in the cement reaction with water.

2.2.3 Water absorbability of bamboo

Hejazi et al. (2012) and Sharma (2014) mentioned that natural fibers have typical characteristic due to cellulose content, i.e. hydrophilic nature. This characteristic leads the fibers to absorb water. The higher content of cellulose provides higher water absorbability (Rashdi et al., 2010). While absorbing water, natural fiber is able to penetrate to soil mixture. It increases the interaction between particles in the soil and hence the density of the mixture. However, constant moisture is required to prevent loss of absorbed water in drying condition. This condition causes the shrinkage of fibers and provides void in the interface between fibers and soil (Hejazi et al., 2012). Munoz and Garcia-Manrique (2015) agreed that water absorption of natural fiber affects positively to the tensile strength of the composite material. However, increasing water absorption also has negative trend to the flexural failure. Thus, water absorbability of natural material is required to be adjusted at the proper application. In addition, natural fiber requires treatment such as chemical modification to prevent much absorbed water by the fiber, increase interface adhesion between fiber and matrix/composite material, and delay the biodegradability of natural material. The chemical treatments applied in some studies and applications were alkali, silane, acetylation, benzoylation, acrylation and acrylonitrile grafting, maleated coupling agents, permanganate, peroxide, isocyanate, stearic acid, sodium chlorite, triazine, fatty acid derivate (oleoyl chloride) and fungal (Kabir et al., 2012). Cement addition in the study of Huang et al. (2011) and Koga et al. (2016) was also aimed to treat bamboo chips as natural fiber in the geotechnical application.

In order to determine the water absorbability, immersion test to the fibers was adapted by some researchers. ASTM D 570-98 was used as the standard test method by Rashdi et al. (2010) and Sharma (2014) to conduct the water absorbability test. However, this method is appropriate to the intact material with large dimension which can be easily drowned and immersed in water. The difference weight before and after immersion was measured to calculate absorbed water by material.

2.2.4 Utilization of bamboo flakes and bamboo chips

This study focused on bamboo flakes and bamboo chips utilization. Following the definition by Sharma (2014), bamboo flakes and bamboo chips can be classified as discontinuous or short fiber due to its size. This type of fiber has a length shorter than 100 times of its diameter. The advantages of utilization of short fibers are low cost, simple production process, and easy application to generate homogenous mixture. In application, bamboo flakes and bamboo chips are utilized in the randomly distributed fiber-mixture. In the form of bamboo chips combined with cement, Huang et al. (2011) and Koga et al. (2016) focused in the improvement of soft ground with low bearing capacity, whereas Saki et al. (2013) investigated the increasing erosion resistance. Moreover, Sato et al. (2014) studied bamboo chips and flakes utilization in high water content of excavated mud. However, the combination between pozzolanic content of cement and high water absorbability of bamboo chips in the poorly graded sand under saturated condition has not been investigated yet.

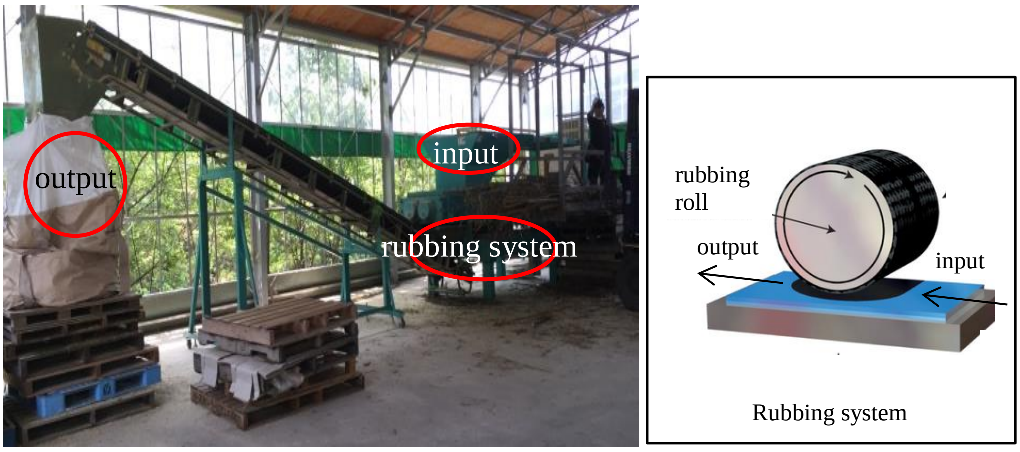
2.3 Research objectives

Focusing on the investigation to the physical properties, micro structure, and water absorbability, bamboo flakes and bamboo chips were evaluated. In this chapter, the simple apparatus and procedure to measure the water absorbability of bamboo flakes and bamboo chips was developed. In addition, variation of bamboo flakes and bamboo chips type and content was conducted in specimen preparation to understand the effect of each parameter to the mechanical properties obtained by static triaxial test. One of the bamboo material types, either bamboo flakes or bamboo chips, was selected as the optimum type in the poorly graded sandy soil improvement based on the results. Furthermore, the conclusion of this chapter will be utilized as the one parameter constantly kept in the next chapter.

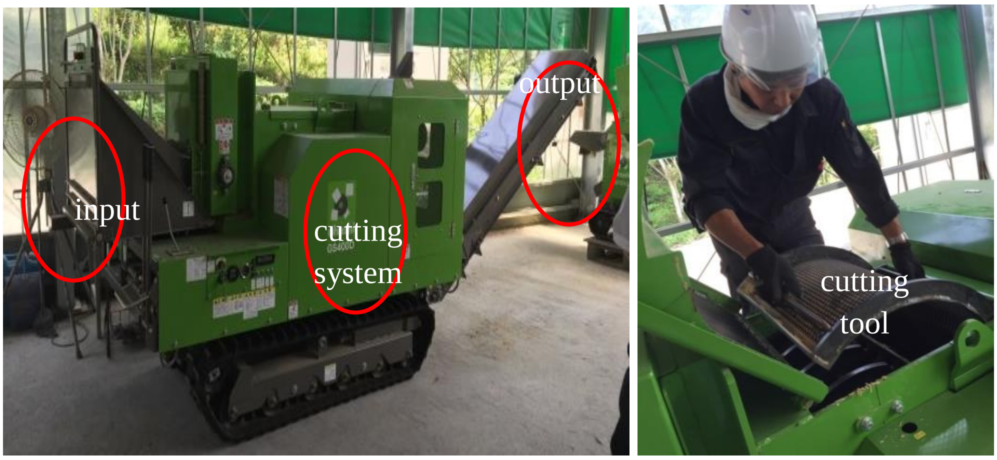
2.4 Properties of bamboo flakes and bamboo chips

2.4.1 Manufacturing process

Bamboo materials are made from bamboo culm produced by using rubbing and cutting machine. Bamboo materials are obtained from Nouken Sangyou Co. Ltd. in Itoshima, Japan. In this study, there are two types of bamboo material based on production process. In accordance with the name of machine, rubbing machine, as shown in Fig. 2.2(a), uses rubbing process for producing bamboo flakes, whereas cutting machine shown in Fig. 2.2(b) uses cutting process in bamboo chips production. Size of bamboo chips can be maintained by replacing cutting tool shown in Fig. 2.3 as the required size. In this study, bamboo chips used are 6 mm and 10 mm bamboo chips based on the longest size of chips. Types of bamboo materials used in this study can be seen in Fig. 2.3.



(a)



(b) (c)

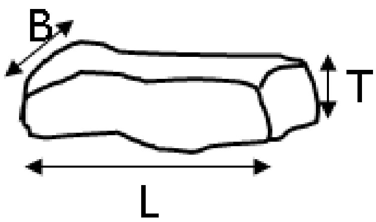
Figure 2.2. (a) Rubbing machine, (b) cutting machine, and (c) cutting tool (Photos were taken in Nouken Sangyou Co. Ltd).

(a) (b) (c)

Figure 2.3. Bamboo chips (a) bamboo flakes, (b) 6 mm bamboo chips, and (c) 10 mm bamboo chips.

2.4.2 Elongation and flatness ratio

This quantification of physical properties of bamboo materials is important to investigate the effect of shape in the mixture. The optimum shape is expected to lead the increasing strength due to the interaction among particles in the mixture due to the shape characteristic. Sieving analysis is difficult to be conducted due to its irregular shape. In this study, physical characterization of bamboo materials was performed by elongation and flatness ratio. Elongation ratio is a ratio between intermediate and shortest length of bamboo material particle, whereas flatness ratio is the ratio between shortest and longest length. This definition is described in Fig. 2.4. Particle length measurement was conducted by using a digital caliper.

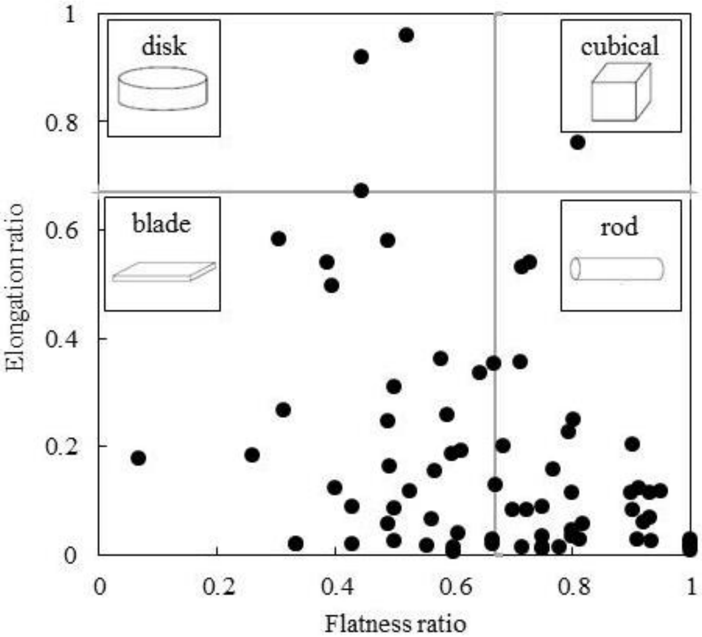


E_r = elongation ratio
= B/L
F_r = flatness ratio
= T/B

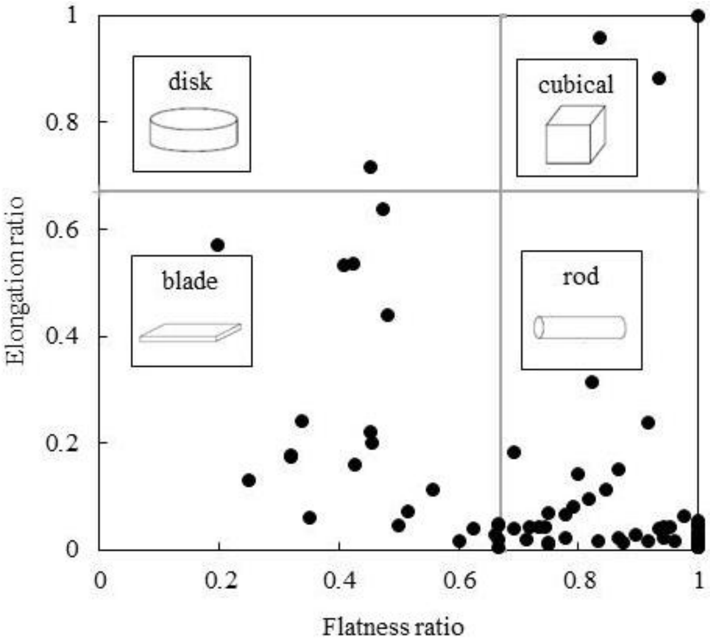
Figure 2.4. Description of elongation and flatness ratios.

Based on the elongation and flatness ratio parameters, particles are divided to be four shapes, i.e. disk, cubical, blade, and rod. The limit of these shapes is 2/3 value of each parameter. Janoo (1998) described the shapes based on aggregate point of view. However, this description can be adopted in case of wood and bamboo material. Disc is slabby in appearance but not elongated, equidimensional (cubic) is neither slabby appearance nor elongated, blade is slabby appearance, and rod is elongated but not slabby in appearance. In the densification process, each shape of particle has typical characteristic in mixture. However, in aggregate point of view, cubical shape was proposed as the optimum shape for increasing the dense configuration in the mixture (Chen et al., 2005). This information was also considered in investigation of physical characteristic of bamboo flakes and chips.

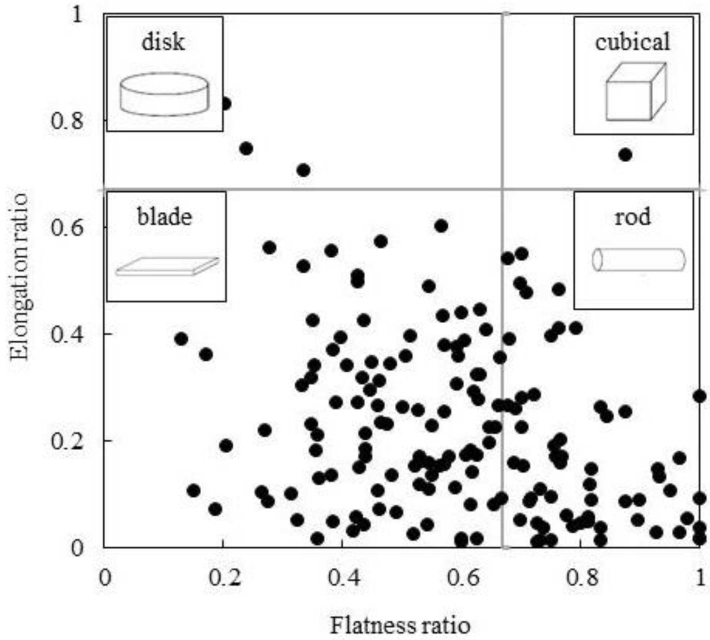
Both types of bamboo chips have same dominant shape, i.e. blade and rod. It can be seen in Fig. 2.5 that depicts the elongation and flatness ratio of bamboo chips. However, 6 mm bamboo chips have cubical shape and its size is smaller, so the compaction process of specimen with 6 mm bamboo chips content is expected to be easier. In addition, cubical shape as the optimum shape in the mixture is expected to increase the interaction among soil, cement and bamboo itself. Furthermore, the increasing strength is also expected by this shape.


disk
cubical
blade
rod
Elongation ratio
Flatness ratio
0
0.2
0.4
0.6
0.8
1

(a)


disk
cubical
blade
rod
Elongation ratio
Flatness ratio
0
0.2
0.4
0.6
0.8
1

(b)

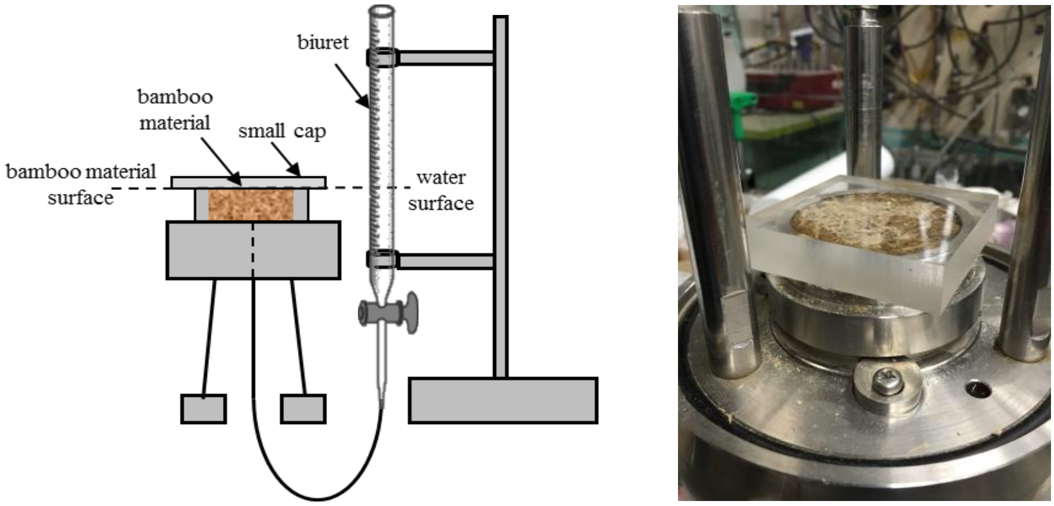


(c)

Figure 2.5. Elongation and flatness ratio of (a) bamboo flakes, (b) 6 mm, and (c) 10 mm bamboo chips.

2.4.3 Water absorbability

As mentioned above, method to determine water absorbability test widely used is immersion test (ASTM D 470-98). However, this test is not reliable for small size material. In addition, buoyant characteristic of natural material causes improper immersion. Based on this reason, water absorbability test to the constant volume of specimen was developed (Fig. 2.6(a)). The sample material was prepared in the form of cylinder specimen. The dimensions of sample are 6 cm diameter and 1.5 cm height. The initial water content was kept less than 5%. Bulk density of the bamboo material is about 0.2 gram/cm^3. A simple procedure of the absorbability test was conducted by connecting the bamboo material cylinder with biuret contains distilled water. The scheme of the apparatus can be seen in Fig. 2.6. Water flowed to the bottom of bamboo material. At the same time, upper part of bamboo material was detained in order to keep the volume by using small cap to avoid the over pressure. Pressure of the cap is 0.03 kPa. Water surface in biuret was maintained as high as bamboo material surface during the test. The decreasing water in biuret is the absorbed water volume. Tests were conducted for 90 minutes. Result of this test provides the absorbability tendency in short term. Calculation of absorbed water index was conducted to provide understanding and comparison among three types of bamboo material. Absorbed water index is ratio between the decreasing water in biuret and volume of bamboo material.



(a) (b)

Figure 2.6. (a) Scheme of absorbability test apparatus and (b) sample specimen in the test apparatus.

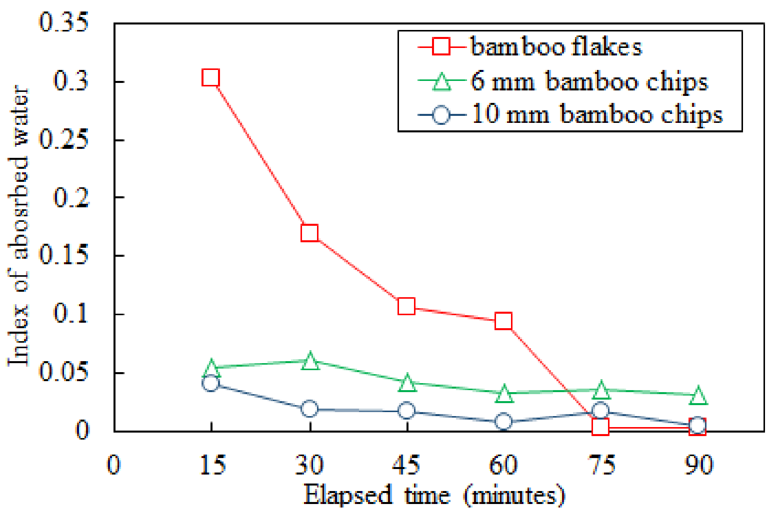


Figure 2.7. Absorbed water index of bamboo material in 90 minutes.

The absorbability of bamboo materials provides potential to decrease the excess pore water pressure of soil mixture in undrained condition during loading. Figure 2.7 shows the tendency of bamboo materials absorbability. Based on the test result, absorbed water of bamboo flakes is the highest for the first 60 minutes, but the value significantly decreases under absorbability value of bamboo chips after this point. It proves that structure of bamboo materials affects the tendency. It can be approved that the rubbing process in production of bamboo flakes causes the outer surface of bamboo culm is exfoliated. Thus, bamboo flakes can easily absorb water and saturated in a short time. Analogous to this, the cutting process in the production of bamboo chips do not change the structure of bamboo culm, but only cut into smaller pieces. It causes the outer part of the bamboo culm still exist and provides longer duration to absorb water. In addition, the comparison between the two types of bamboo chips is also shown in Fig. 2.7. Water absorbability of 6 mm bamboo chips is about 25% higher than 10 mm bamboo chips at the same time test. In the larger size, water requires longer time to saturate. This result proves that size factor also has effect to the water absorbability. This conclusion was strengthened by the result of bamboo absorption investigation by Junior et al. (2009). They conducted the test to the larger size of cut bamboo. Their study concluded that the mean of relative absorption volume of bamboo with 1.5 cm x 1.5 cm dimension of cut bamboo is about 4%. The maximum absorption rate for this size of cut bamboo is about 18 hours. This means that the larger size of cut bamboo provides higher water absorbability, but in the longer time.

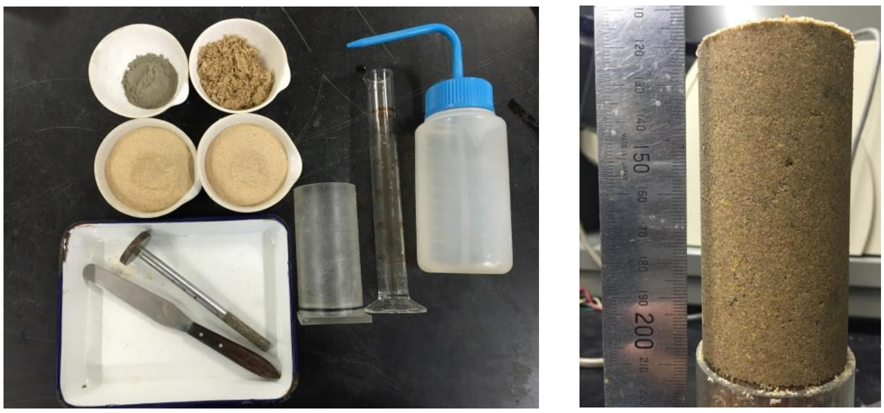
2.5 Methodology

In this study, specimen is mixture of 35% relative density (D_r) of Toyoura sand, variation of bamboo materials type and cement content. The dimensions of specimen are 50 mm diameter and 100 mm height in cylinder. Cement used in this study is Ordinary Portland Cement (OPC). It was obtained from cement company in Japan. In the AASHTO soil classification, Toyoura sand used in this study is classified in A-3 namely non-plastic sand soil. Portland Cement Association

(1956) provided guideline to determine the optimum cement content for stabilization purpose. Percentage of cement suggested for A-3 soil is 7-11%. This guideline is used for the rough range in practice and research activities. In this study, to reduce cement utilization in soil improvement and to obtain the information regarding tendency of BLAsh effect in the small amount of cement content, cement percentage were chosen less than suggested amount in guideline, i.e. less than 4%. The variations are presented in Table 2.1. Water addition of 20% was decided based on the preliminary trial considering the workability reason. The percentages of bamboo materials, cement, and water are referenced to dry mass of Toyoura sand. Specimen was prepared by mixing soil, cement, and bamboo materials in dry condition into a homogeneous color mixture then pour water into the mixture. Compaction was conducted in acrylic cylinder (Fig. 2.8(a)). Generally, pozzolanic materials have the ability in hardening process by hydration over the time. Singh et al. (2000) and Shi and Day (2001) investigated the curing time effect of baggage ash as natural pozzolan blended with cement and lime-pozzolanic cement mixture in varied conditions, respectively. They stated that the high increment of compressive strength and pozzolanic reaction rate are in the early stage of curing time, i.e. 7 days or less. The strength and reaction are still increasing after 7 days, but the increment is not significant approaching 28 days. It shows that the specimen age of 28 days is estimated as the optimum age by its nearly constant strength. The objective of this study compares among the mixture variations during hardening process. By this reason, short term is applied for curing time period in all chapters. In this chapter, the specimens were cured for 3, 7 and 14 days. After curing, acrylic cylinder was removed (Fig. 2.8(b)).

Table 2.1. Specimen Variations

Cement content	Bamboo material	Mixture code	Curing time and type of test
0%	0%	T	0 days Triaxial $\overline{CU}$
	1% bamboo flakes	TB_f1	7 days SEM test
	1% 6mm bamboo chips	TB_61	
	1% 10mm bamboo chips	$TB_{10}1$	
2%	1% bamboo flakes	$TC2B_f1$	3, 7 and 14 days Triaxial $\overline{CU}$
	1% 6mm bamboo chips	$TC2B_61$	
	1% 10mm bamboo chips	$TC2B_{10}1$	
4%	1% bamboo flakes	$TC4B_f1$	
	1% 6mm bamboo chips	$TC4B_61$	
	1% 10mm bamboo chips	$TC4B_{10}1$	
	0%	TC4	7 and 14 days Triaxial $\overline{CU}$



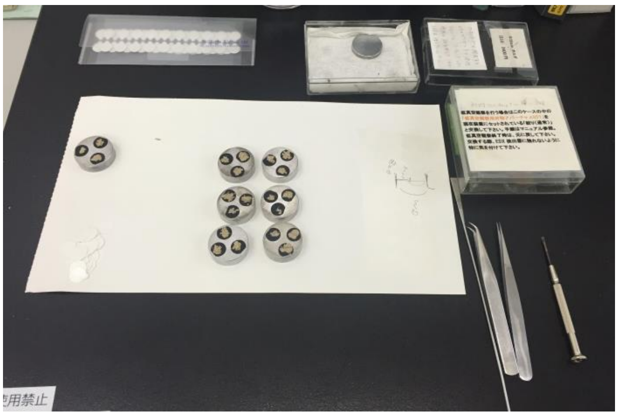
(a) (b)

Figure 2.8. (a) Specimen preparation before mixing and (b) specimen of the test after curing time.

Consolidated-undrained method of triaxial test with the pore water pressure measurement during loading was conducted based on ASTM 4767-02 (Fig. 2.9(a)). In triaxial test, to obtain a high degree of saturation, deaired water was circulated in the specimen by using double negative pressure method. In addition, back pressure of 200 kPa was applied. B-values of more than 0.9 were observed in all. The test was performed at 50, 100, and 150 kPa of confining pressure. Strain was controlled after isotropic consolidation. The samples were executed by applying a monotonic axial load with a strain rate of 0.1%/min. In addition, for determining the particle interactions in the mixture, SEM (Scanning Electron Microscopic) test using SS-550 apparatus (Fig. 2.10(b)) was conducted.

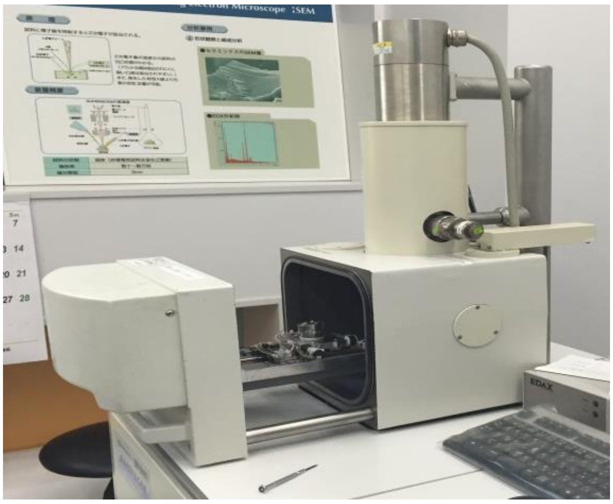
(a) (b)

Figure 2.9. (a) Static triaxial test apparatus and (b) specimen after loading.



(a)

(b)



(c)

Figure 2.10. (a) Specimen of SEM test, (b) SEM super scan (SS-550) apparatus, and (c) specimen chamber.

2.6 Comparison between bamboo flakes and chips on cemented sandy soil mixture

In ASTM 4767-11, “failure is often taken to correspond to the maximum principal stress difference (maximum deviator stress, $q_{max} = \sigma_1 - \sigma_3$) attained or the principal stress difference (deviator stress) at 15% axial strain, whichever is obtained first during the performance of a test”. Based on this definition, this study utilized failure point to compare some variation results. Failure point was chosen at 15% axial strain as its maximum deviator stress (q_{max}) due to the hardening model of the mixture shown by increasing curve in the stress-strain relationship. Figure 2.11 shows one of static triaxial results.

2.6.1 Effect of bamboo materials type

As previously mentioned, production process of bamboo materials has significant effect to its structure. Furthermore, the structure of bamboo materials will also affect its performance in the mixture. Result of triaxial and SEM test of 1% addition of bamboo materials type variation in the mixture without cement addition are shown in the Figs. 2.12 and 2.13, respectively.

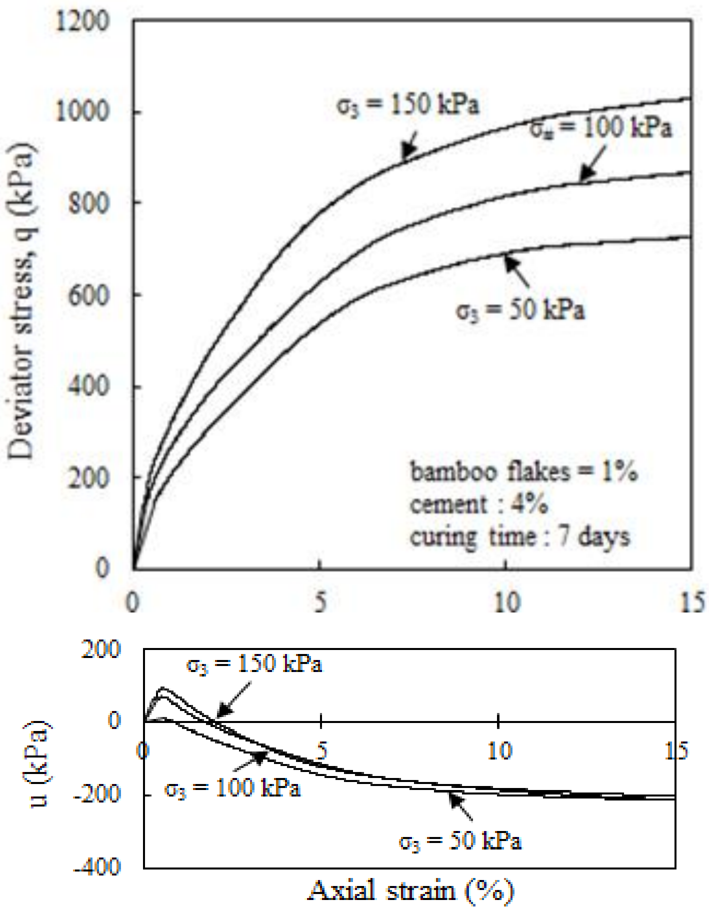


Figure 2.11. Stress-strain relationship and pore water pressure of mixture with 4% cement and 1% bamboo flakes (TC4B$_f$1).

In the small confining pressure, bamboo flakes addition provides higher value of q_{max}. It can be approved that bamboo flakes type is not suitable for high confining pressure due to its structure.

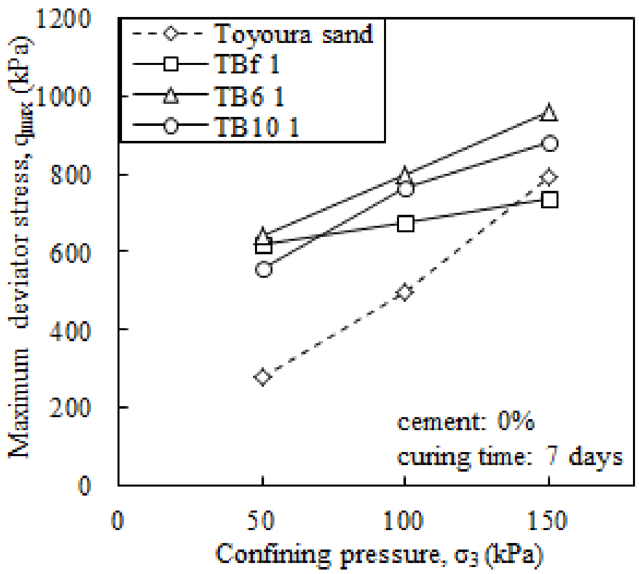
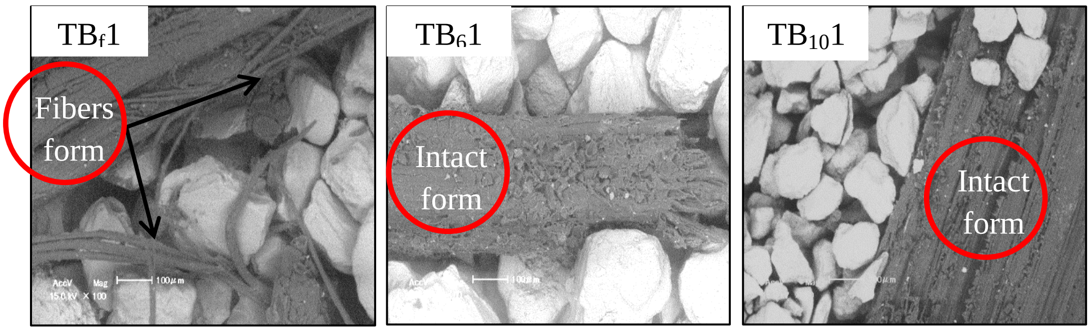


Figure 2.12. Comparison of q_{max} of bamboo materials type variation.



(a) (b) (c)

Figure 2.13. Result of SEM analysis of non-cemented specimen with addition of (a) bamboo flakes, (b) 6 mm, and (c) 10 mm bamboo chips.

Based on Fig. 2.13, result of SEM test shows that bamboo flakes consists of fibers form (Fig. 2.13(a)), whereas bamboo chips is in the form of intact structure (Fig. 2.13(b)). Bamboo flakes has lower performance against high pressure compared to bamboo chips due to its form. The 6 mm bamboo chips have highest performance to increase q_{max}. It shows accordance with previous discussion. Size of bamboo chips has also main effect to the performance in the mixture.

2.6.2 Effect of cement content

Effect of cement content was observed and presented in Fig. 2.14. All types of bamboo materials has same tendency in increasing q_{max} along with cement content addition. It can be concluded that higher cement content provides higher strength. Cement addition is intended to bind among particle in the mixture by its ability to react with water. Chemical and physical change will be occurred in the presence of cement and water. The paste, as a result of cementation reaction between cement and water, is able to fill void in mixture. In addition, increasing strength is also provided along the time called as the hardening process (Powers, 1935).

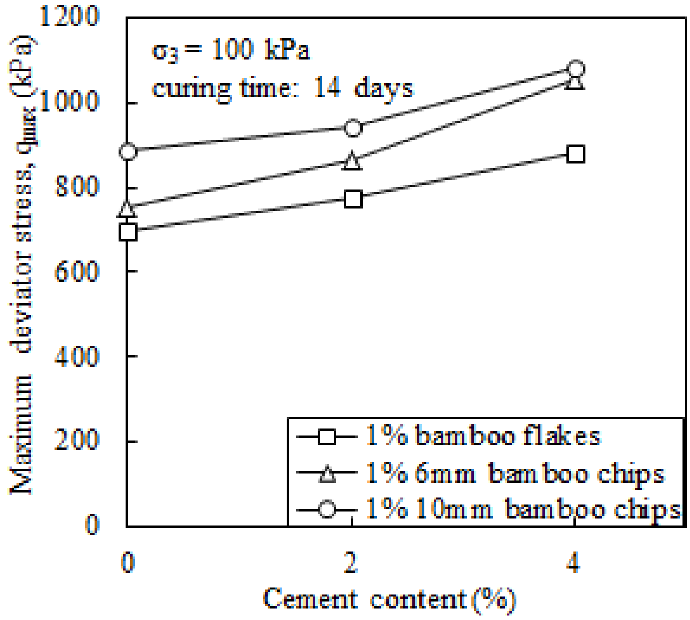


Figure 2.14. Comparison of maximum deviator stress of cement content variation in 1% content of bamboo materials after 14 curing time.

On the other hand, sandy soil and bamboo material do not have ability to bind each other. Thus, utilization of cement content is required to increase the interaction among particles. Cement effect also can be seen in the SEM test result in Fig. 2.15. Figure 2.15(b) and (d) shows that the voids in the mixture were filled more by cement paste compared to Fig. 2.15(a) and (c).

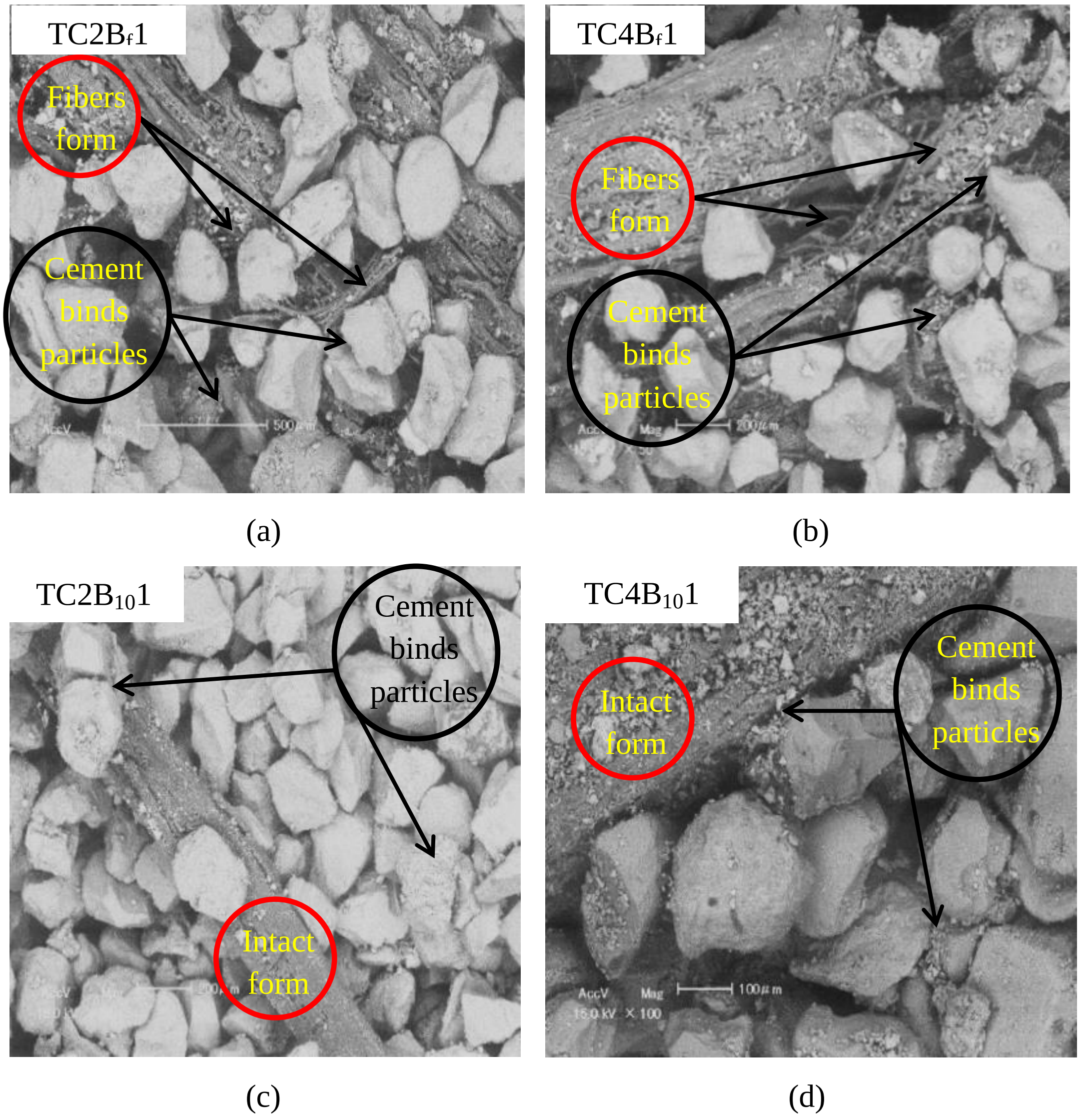


Figure 2.15. Result of SEM analysis of specimen variation with addition of (a) 2% cement and 1% bamboo flakes, (b) 4% cement and 1% bamboo flakes, (c) 2% cement and 1% 10 mm bamboo chips, and (d) 4% cement and 1% 10 mm bamboo chips.

Regarding the type of bamboo material Fig. 2.14 also shows that bamboo flakes provided lowest value of q_{max}, whereas bamboo chips with longest size of 10 mm presented highest strength. Fibers structure of bamboo flakes provides void that can be filled by cement paste for sticking all particles in mixture. However, the fiber form is less reliable to reinforce the mixture compared to bamboo chips type. Based on this result, it can be concluded that the production process affect this result.

2.6.3 Effect of curing time

Curing time effect was observed to determine interaction between bamboo material and cement in view point of time dependency. In Fig. 2.16, for both 2% and 4% cement addition, 10 mm bamboo chips and bamboo flakes provide highest and lowest q_{max} in three curing time variations, respectively. Each type of bamboo material also shows different performance in increment of q_{max} shown in Fig. 2.17. The increment of q_{max} is presented to understand the increasing strength along the time. After 7 days curing time, bamboo flakes provided highest increment of q_{max} referenced by 3 days curing time. For short period, it shows good interaction between cement and bamboo flakes due to its fibers structure.

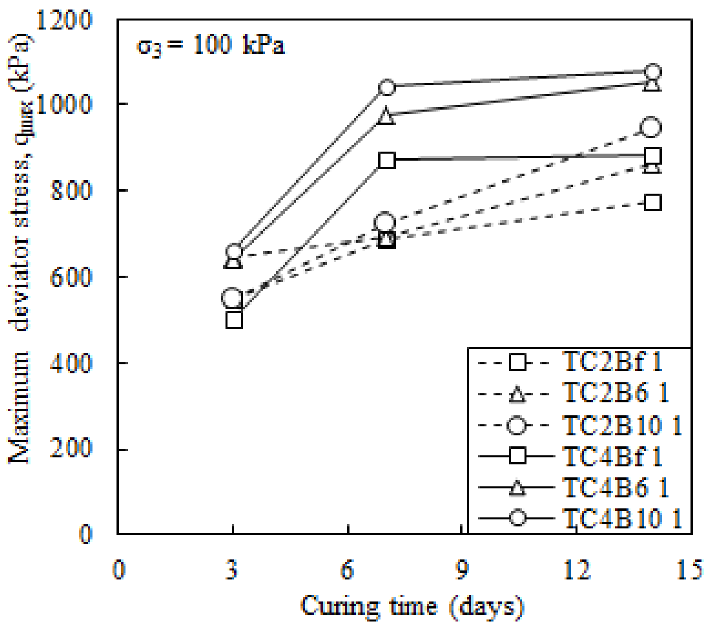


Figure 2.16. Comparison of q_{max} of curing time variation.

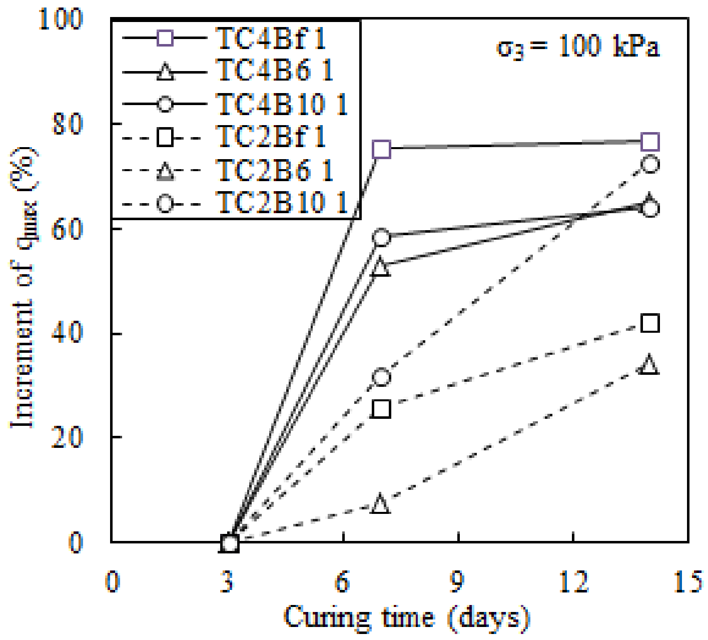


Figure 2.17. Increment of q_{max} referenced by 3 days curing time.

However, in the mixture with 2% cement addition, highest increment was presented by 10 mm bamboo chips addition, whereas bamboo flakes addition showed second higher increment. In the 4% cement addition, consistent tendency was shown by all bamboo material type addition that significant increment was reached in the short time. Thus, for short term application, high content of cement with bamboo flakes can be relied. However, for long term, bamboo chips are more suitable although with the small amount of cement. It can be approved by the ability of bamboo flakes absorb water more than bamboo material in short time. It causes the increasing moisture content of bamboo flakes is more rapid. This is related to the decreasing strength of bamboo material by increasing moisture content stated by Jiang et al. (2012) and Li (2009). Therefore, bamboo chips are concluded has higher potential in reinforcement of cemented sandy soil, especially for long term purpose.

2.7 Conclusions

Utilization of bamboo flakes and bamboo chips in geotechnical field was reviewed. In order to determine the optimum type between bamboo flakes and bamboo chips, water absorbability test apparatus was developed. In the constant volume of bamboo flakes and bamboo chips, relationship between water absorbability and elapsed time was determined using this simple test apparatus. In addition, physical characteristic, mechanical properties, and microscopic analysis of bamboo material addition in cemented sandy soil improvement were examined by elongation-flatness ratio, static triaxial test, and Scanning Electron Microscopic (SEM) test, respectively. It was found that cutting machine produces intact structure of bamboo chips, whereas rubbing machine produces fiber structure of bamboo flakes. The form of structure affects the water absorbability and mechanical properties of bamboo material in cemented sandy soil. Based on the comparison, intact form of bamboo chips provides higher performance compared to bamboo flakes by the consistent water absorbability and the higher shear strength in cemented sandy soil mixture. Based on this conclusion, next chapters will focuses on the discussion of mixture using bamboo chips in other investigations.

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CHAPTER 3

UTILIZATION OF BAMBOO CHIPS ON PERMEABILITY AND DILATIVE BEHAVIOR OF CEMENTED SANDY SOIL

3.1 Introduction

This chapter focuses on the utilization of bamboo chips as the conclusion of previous chapter. By varying the mixtures and curing time under permeability and untrained static or monotonic triaxial test, evaluation of bamboo chips type and content effectiveness in sandy soil improvement is presented. This chapter asserts information on whether bamboo chips are able to be utilized as cement replacement or as reinforcement of cemented sandy soil mixture. The conclusions of this chapter, i.e. optimum type and content of bamboo chips, have a main role for the further investigation in the next chapter.

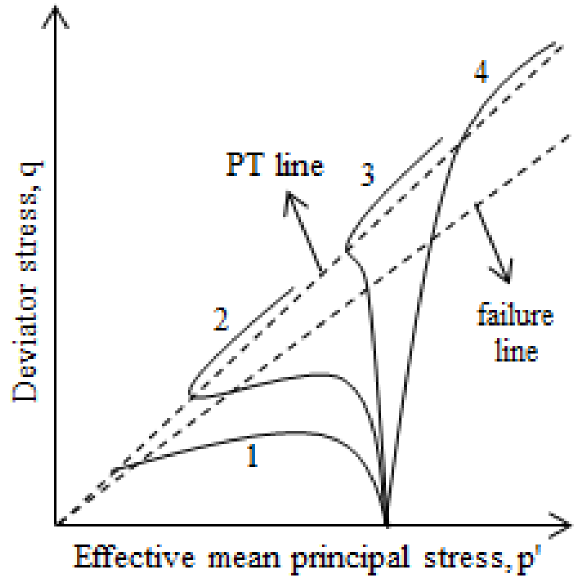
3.2 Literature review

3.2.1 Definition of static liquefaction

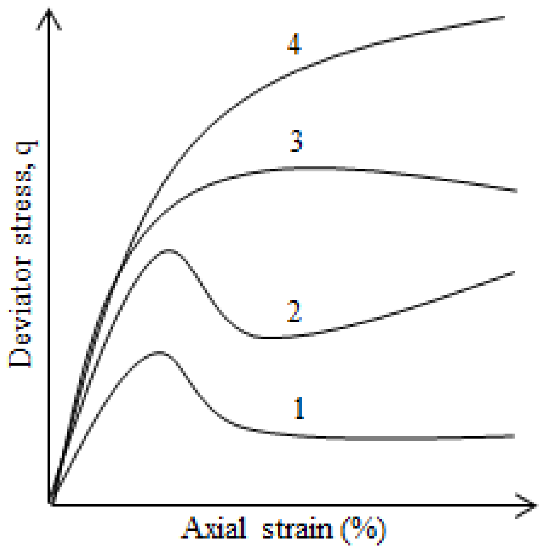
In triaxial compression test, monotonic/static loading increases pore water pressure and thus decreasing effective stress. Static liquefaction was developed as a large shear phenomenon of soil mass at low confining pressure under static triaxial test (Ibsen, 1998). This phenomenon is a typical characteristic of loose and poorly graded sand in saturated condition. When the strain level is large enough, soil samples under sharing tend to be in a state of continuous deformation under constant shear and normal stress. Furthermore, static liquefaction might be studied to obtain a better understanding of the occurrence of flow type of failure (Salamatpoor and Salamatpoor, 2014).

3.2.2 Dilative behavior of sandy soil

In undrained condition, sandy soil has three main behaviors in monotonic triaxial test, i.e. dilative ("positive dilatancy"), limited/partially-contractive, and fully contractive ("negative dilatancy") (Hyodo et al., 1994; Ibsen, 1998; Igwe et al., 2004; Ishihara et al., 1975; Jafarian et al., 2013; Mohamad and Dobry, 1986; and Vaid and Chern, 1983). Relative density, confining pressure and static shear stress are factors affecting this behavior (Jefferies and Been, 2006 and Salamatpoor and Salamatpoor, 2014). Based on Figs. 3.1(a) and 3.1(b), contractive behavior is shown by Curve 1. In this behavior, increasing deviator stress is followed by its decreasing to constant value called by steady state or residual state (Hyodo et al., 1994). Limited/partially-contractive is presented by Curve 2. This behavior is shown by "elbow" shape formed by reaching the maximum deviator stress then together with the strain softening emerged at a certain stage of shear to a minimum deviator stress before turned and ascended along the failure line (Hyodo et al., 1994; Ibsen, 1998; Igwe et al., 2004; Ishihara et al., 1975; Jafarian et al., 2013; and Mohamad and Dobry, 1986). The elbow is observed in this study as comparison of dilation tendency. Based on the Fig. 3.1(a), elbow is shown by Curve 3, but in Fig. 3.1(b), relationship between deviator stress and axial strain of Curve 3 shows increasing deviator stress during loading. It shows flow tendency, but hardening is occurred toward dilation. Dilative behavior is shown by Curve 4. Increasing deviator stress is always occurred during loading.



(a)



(b)

Figure 3.1. Flow deformation behavior of sand in monotonic test (a) effective stress path and (b) relationship between deviator stress and axial strain. (Modified after Hyodo et.al., 1994 and Mohamad and Dobry, 1986).

3.2.3 Effect of permeability to dilative behavior

Besides density, confining pressure and static shear stress as the main factors mentioned above, Ibsen (1998) explained that coefficient of permeability also affects the dilative behavior. Rahmani et al. (2012) conducted some simulations using numerical analysis on liquefaction phenomenon. They concluded about the importance of soil permeability coefficient to predict the pore pressure and displacement. Moreover, Ramirez (2010) showed the sensitivity of loose and poorly graded sand behavior due to permeability value. It was found that the higher soil permeability, the weaker soil dilation. Nevertheless, if the coefficient of permeability becomes too high, the excessive pore pressure is significantly reduced.

3.3 Research objectives

Based on the permeability and static triaxial test, effect of bamboo chips to the dilative behavior of cemented sandy soil was investigated. In addition, in the variation of two sizes of bamboo chip, content of bamboo chips, cement content, and curing time, optimum size of bamboo chips was expected to be obtained.

3.4 Methodology

Bamboo chips are made from bamboo rod produced by using cutting machine. In this chapter, there are two types of bamboo chips based on the longest size of chips, i.e. 6 mm and 10 mm, shown in Figs. 3.2(a) and 3.2(b), respectively.

In this chapter, specimen was prepared with same treatment as the specimen preparation in Chapter 2. Mixture contains Toyoura sand as the reference material to the content of other materials (water, bamboo chips, and cement). Relative density (D_r) was kept equals 35%. The dimensions of specimen are 50 mm diameter and 100 mm height in cylinder. Same as the previous chapter, cement used in this study is Ordinary Portland Cement (OPC). The variations are presented in Table 3.1. Water addition of 20% was decided based on the preliminary trial considering the workability reason. The percentages of bamboo chip, cement, and water are referenced to dry mass of Toyoura sand. Specimen was prepared by mixing soil, cement, and bamboo chips in dry condition into a homogeneous color mixture then pour into the mixture. Compaction was conducted in acrylic cylinder. The specimens were cured for 7 and 14 days. After curing, acrylic cylinder was removed. Appearance of 2% content of 6 mm and 10 bamboo chips in sandy soil mixture are shown in Figs. 3.3(a) and 3.3(b), respectively.

(a) (b)

Figure 3.2. Bamboo chips (a) 6 mm and (b) 10 mm.

Table 3.1. Specimen Variations

Type of the test	Curing time (days)	Specimen variations
triaxial $\overline{CU}$, constant head permeability	0	Toyoura sand (T)
	7, 14	T:1% 6 mm bamboo chips (TB_61)
		T:2% 6 mm bamboo chips (TB_62)
		T:1% 10 mm bamboo chips ($TB_{10}1$)
		T:2% 10 mm bamboo chips ($TB_{10}2$)
		T:4%OPC (TC4)
		T:4% OPC:1% 6 mm bamboo chips ($TC4B_61$)
		T:4% OPC:2% 6 mm bamboo chips ($TC4B_62$)
		T:4% OPC:1% 10 mm bamboo chips ($TC4B_{10}1$)
		T:4% OPC:2% 10 mm bamboo chips ($TC4B_{10}2$)

(a) (b)

Figure 3.3. Specimens with 2% of (a) 6 mm bamboo chips (TB_62) and (b) 10 mm bamboo chips ($TB_{10}2$).

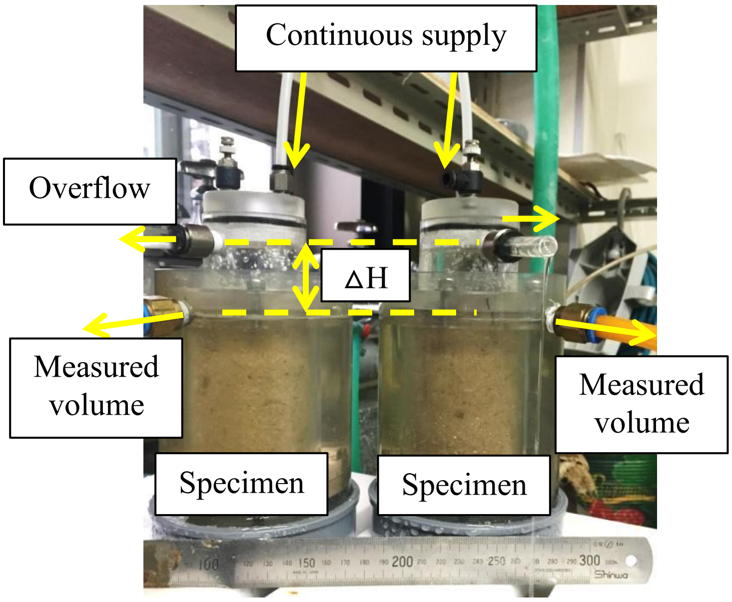


Figure 3.4. Coefficient of permeability apparatus.

Permeability (Fig.3.4) and triaxial test were conducted by using constant head method (ASTM 2434-68) and consolidated-undrained method with the pore water pressure measurement during loading (ASTM 4767-11), respectively. In triaxial test, same procedure as the triaxial test in Chapter 2, to obtain a high degree of saturation, deaired water was circulated in the specimen by using double negative pressure method. In addition, back pressure of 200 kPa was applied. B-values of more than 0.9 were observed in all. The test was performed at 50, 100, and 150 kPa of confining pressure. Strain was controlled after isotropic consolidation. The samples were executed by applying a monotonic axial load with a strain rate of 0.1%/min. Stress parameters p' and q are used for representing the effective mean principal stress, $p' = (\sigma'_1 + 2\sigma'_3)/3$, and the deviator stress, $q = \sigma'_1 - \sigma'_3$, respectively. Following same concept of maximum deviator stress (q_{max}) in ASTM 4767-11 stated in the previous chapter. Definition of q_{max} is the peak value of deviator stress in the stress-strain curve of the triaxial test result. But, if there is no peak in the curve, deviator stress at 15% ($q_{at15\%}$) of strain is selected as the q_{max}. The q_{max} term is consistently used in this study.

3.5 Results and discussions

3.5.1 Coefficient of permeability

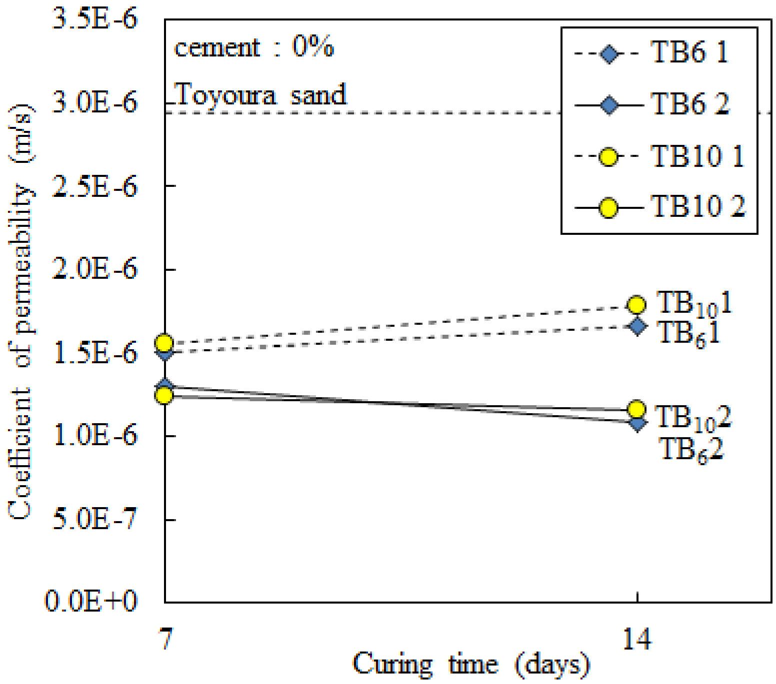
In liquefaction phenomenon, pore water pressure of loose sandy soil increases in short time due to earthquake loading. This increasing pore water pressure causes zero effective shear strength. The dissipation of pore water pressure is the dominant mechanism after the seismic or earthquake loading ceases. During liquefaction, the soil permeability may increase significantly due to the reduction of contacts among particles causing large displacement. It shows that the larger pore shape, the larger path for water to flow and larger displacement. Thus, the ability of water to flow or drainage that is generally called as coefficient of permeability is the important parameter in the liquefaction phenomenon (Ramirez, 2010). Based on this consideration, to reduce the contractive soil response as main characteristic of liquefiable soil, decrease the coefficient of permeability by bamboo chips is the objective of this research.

Besides its ability to absorb water in the void, bamboo chips are also expected to hamper water to flow in the void. This effect of bamboo chips is able to provide time for water to flow defined as decreasing coefficient of permeability. It can be seen in the result of the permeability test to the mixtures in some variations.

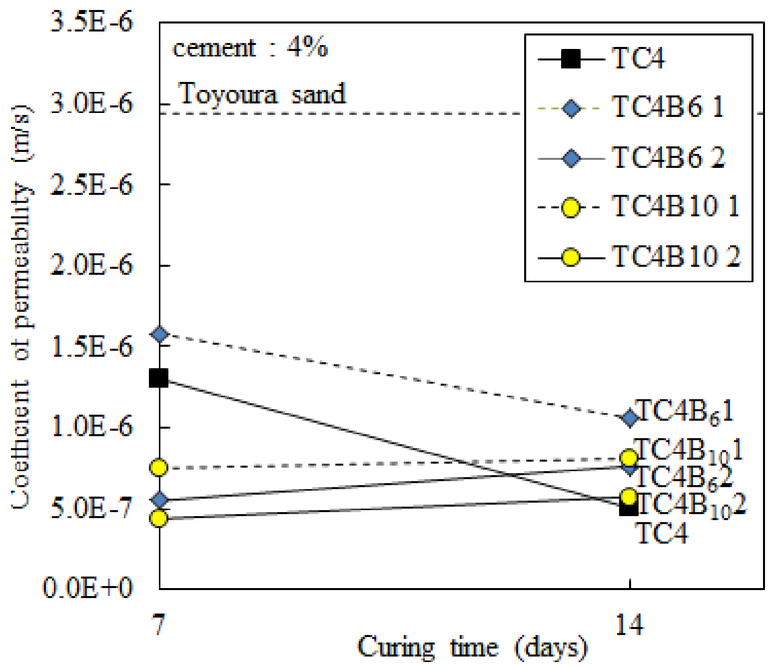
In the mixture without cement, bamboo chips addition provides significant effect to the coefficient of permeability. Figures 3.5(a) and 3.5(b) shows the decreasing of permeability coefficient about 47-58% and 40-63% of bamboo chips addition after 7 days and 14 days curing time compared to Toyoura sand, respectively. Based on this result, size factor of bamboo chips provides slight effect. It can be seen from adjacent lines between 6 mm and 10 mm of bamboo chips on the same percentage content in Fig. 3.5(a). However, the quantity factor and curing time have an influence on the coefficient of permeability. This is indicated by the different slope of the curve between 1% and 2% of cement content in Fig. 3.5(a). The higher content of bamboo chips, the lower of permeability coefficient. Based on the influence of curing time, there is also information that the addition of 1% of bamboo chips gives a negative effect over time. It is because small amount of bamboo chips allows water to saturate in a short time. This result is in contrast to the result of the previous study by Shigematsu et al. (2016). This study concluded that the higher amount of bamboo chips provided higher permeability due to higher void ratio in the mixture by bamboo chips. However, they mixed more than 40% bamboo chips content in the soil. In this study, small amount of bamboo chips was highlighted to provide high strength of soil mixture. There is intersected curve in the 2% of bamboo chips content. It might be due to the human error in the experimental stage during specimen preparation.

Pozzolanic content in cement presents different tendency. This information can be seen in Fig. 3.5(b). The decreasing permeability of the cemented sand soil provides that cementation reaction was occurred. The decreasing void of sand is an effect of the bonding reaction between cement and water. Moreover, bamboo chips additions provide varying tendency. After 7 days curing time, permeability coefficient of the specimen with 1% and 2% content of 10 mm bamboo chips and 2% content of 6 mm bamboo chip are low compared to the cemented sand. Yet, after 14 days curing time, there are increasing tendency. It can be approved that cementation reaction might be hampered due to the presence of the bamboo chips as additive material in large quantities.

Based on the comparison between non cemented and cemented bamboo chips-sandy soil mixture, it can be concluded that cement addition still provide significant improvement of permeability. In addition, factor of size and content of bamboo chips also presents significant effect on the coefficient of permeability. Hence, the 6 mm bamboo chips were concluded able to show the improvement regarding reduction of coefficient of permeability in cemented sandy soil.



(a)



(b)

Figure 3.5. Coefficient of permeability (a) without cement and b) with 4% cement in mixture.

3.5.2 Undrained monotonic triaxial compression behaviour

Dilative behavior of sand soil that represents the tendency of static liquefaction resistance is interpreted by stress path as a result of the monotonic triaxial test. Figures 3.6 and 3.7 depict the test result of Toyoura sand mixed with 4% cement content. Elbow shape that indicates the softening behavior in Fig. 3.6 is not clear. In addition, hardening curve is also shown in Fig. 3.7. This tendency is similar with the Curve 4 in Fig. 3.1. It can be approved that the cemented sand soil has dilative behavior. Based on this result, addition of the bamboo chips in the mixture has to be investigated to obtain the optimum type and content as proposed additive material in order to reinforce and/or substitute cement utilization in the mixture.

In this study, the comparison of the properties contained in the specimen is presented at the 100 kPa of confining pressure application. This boundary provides focus discussion in order to provide understanding of each parameter effect. There are three parameters compared, i.e. variation of bamboo chips size and content, curing time, and cement content. Observation is focused on the stress path behavior, especially on the elbow characteristic line that depicts the dilative behavior of specimen.

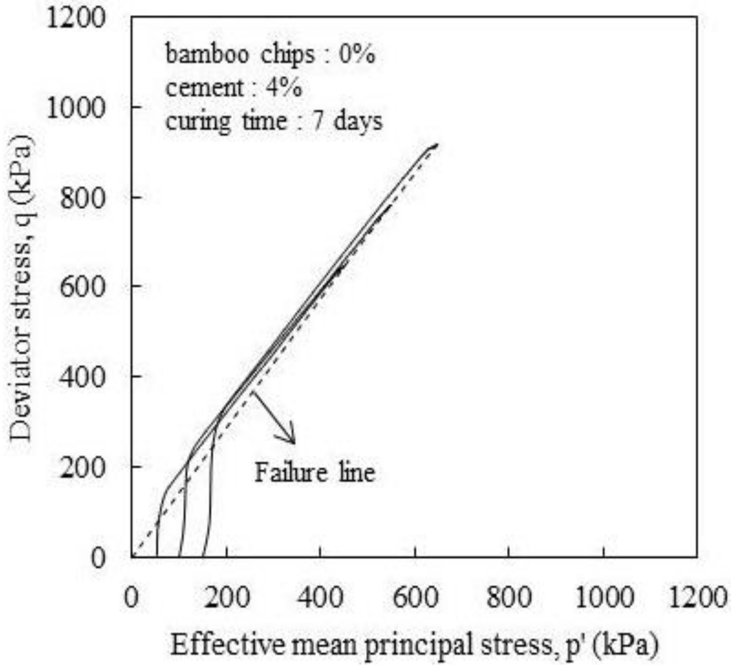
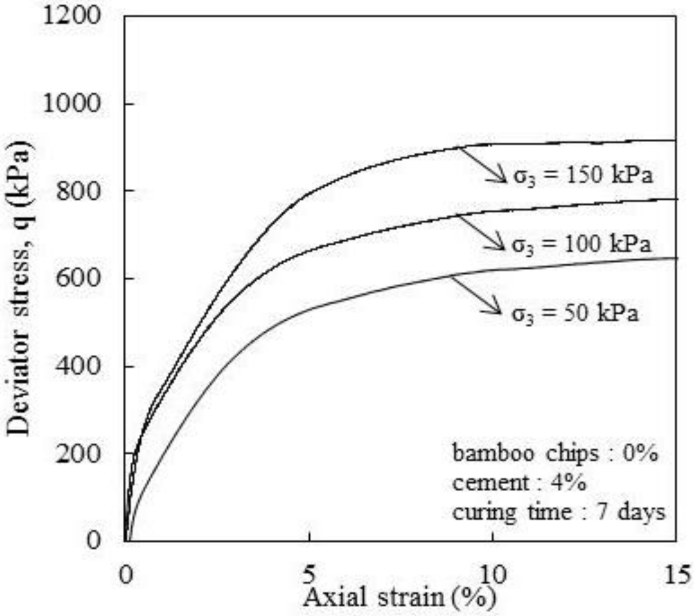


Figure 3.6. Stress path of the cemented sandy soil.



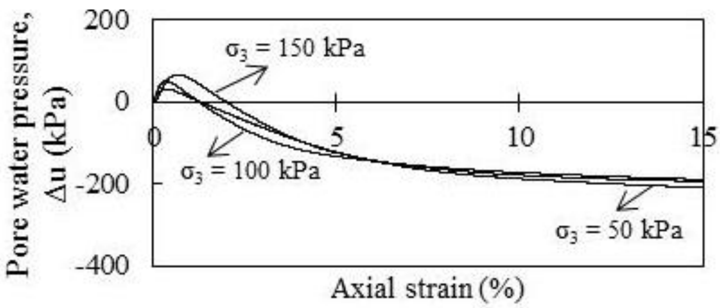


Figure 3.7. Stress-strain relationship and pore water pressure of cemented sandy soil.

Effect of Bamboo Chips Size and Content

In the dilative behavior of cemented sand soil, factor of size and content of bamboo chips has main effect. Based on Fig. 3.8, after 7 days curing time, it can be seen that the highest stress path is reached by addition of 1% content of 10 mm bamboo chips. However, the upright curve is reached by addition of 2% content of 6 mm bamboo chips. It proves that small amount of 10 mm bamboo chips is able to improve the strength of the specimen by its material, while 6 mm bamboo chips allows cement to react with water due to its small size. This conclusion is supported by stress–strain curve shown in Fig. 3.9. The highest maximum deviator stress is shown by $TC4B_{10}2$ mixture. It means that this mixture has highest strength compared to others. However, stress-strain behavior of $TCB_{6}2$ mixture shows improvement during loading. Although maximum deviator stress of this mixture is low, but the 2% content of 6 mm bamboo chips provides reinforcement in the mixture due to its easiness to bind with other particles using cement as a binder, especially during the loading process. Also, this statement is approved in accordance with the absorbability test result discussed in the previous chapter. Water can be easily absorbed by smaller bamboo chips. This can be concluded that cemented reaction is the main factor in addition of small bamboo chips.

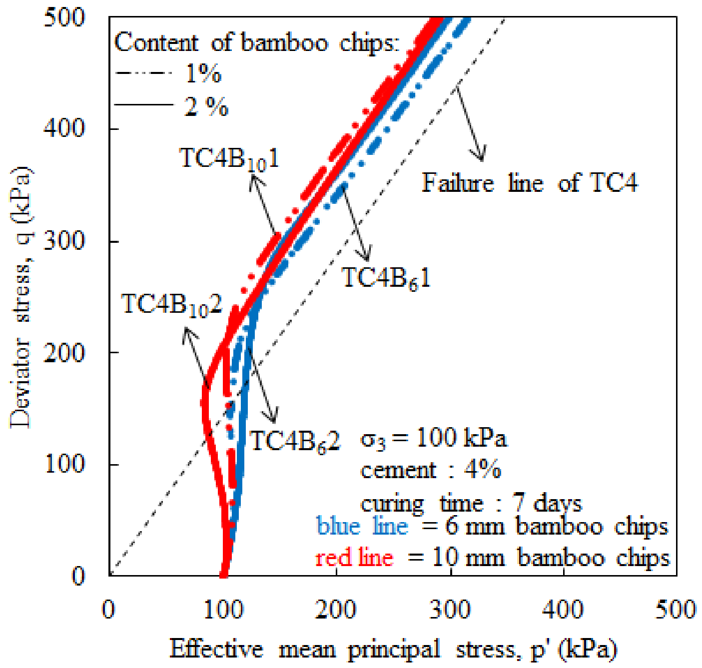
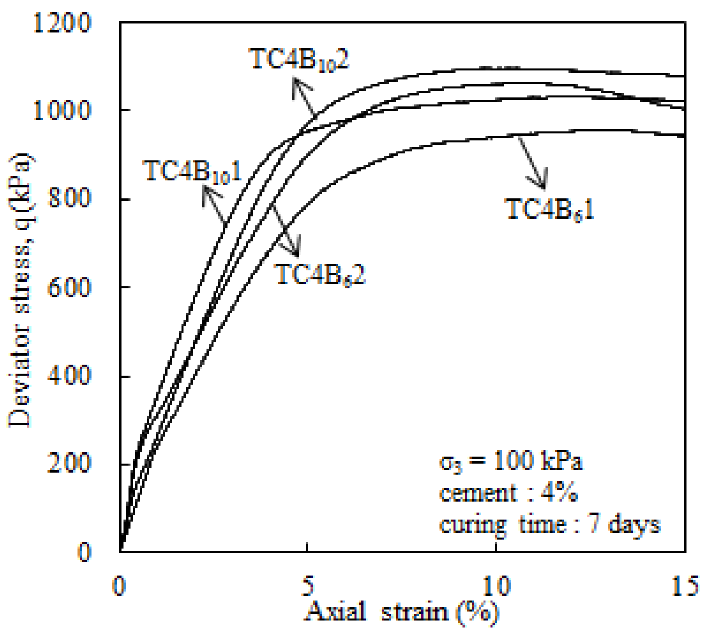


Figure 3.8. Stress path in variation of bamboo chips size and content in cemented sandy soil.



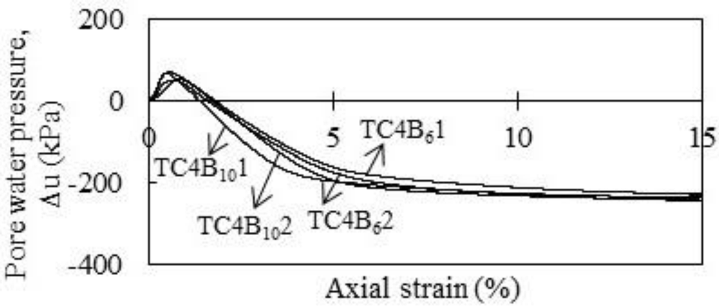


Figure 3.9. Comparison of stress-strain relationship and pore water pressure in variation of size and content of bamboo chips.

Effect of Curing Time

Investigation to the effect of curing time variation is required because there is effect of time dependency to the characteristic of additive materials. Curing time variation conducted in this study are 7 and 14 days. Variation of the curing time can be seen in Figs. 3.10-3.13. This information provides slight differences based on the adjacent curve. Based on observation of elbow shape and characteristic of stress path in Figs. 3.10 and 3.12, after 14 days curing time, improvement of specimen are shown by both types of bamboo chips. Positive tendency of the curing time are also shown in the stress-strain relationship curve in Figs. 3.11 and 3.13.

In this view point of time dependency, variations of bamboo chips size and content still provide effect to the performance of the mixture. Based on the Fig. 3.10, in accordance with the previous discussion, large amount of 6 mm bamboo chips provides positive effect to the mixture shown by upright curve after 7 days curing time. Yet, the opposite result is shown after 14 days curing time, small amount of 6 mm bamboo chips provides better result. This result is approved that after 7 days curing time, interaction between bamboo chips and cement has main part to the characteristic of the specimen. During its curing time, bamboo chips absorb water. After 14 days curing time, in accordance with the result of absorbability and permeability test, larger amount of 6 mm bamboo chips in cemented mixture require short time to be saturated and show negative improvement. This reason can be approved in the relationship between deviator stress and axial strain in Fig. 3.11. The small amount of 6 mm bamboo chips shows similar curve with the Curve 4 in Fig. 3.1(b), whereas large amount of 6 mm bamboo chips shows similar curve with the Curve 3. This means that the higher amount of 6 mm bamboo chips provides softening model instead of hardening.

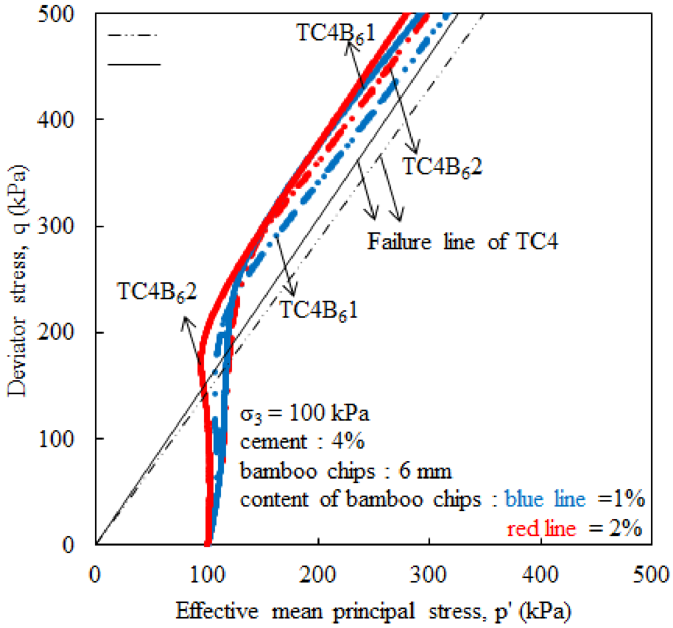


Figure 3.10. Stress path in variation of curing time (6 mm bamboo chips).

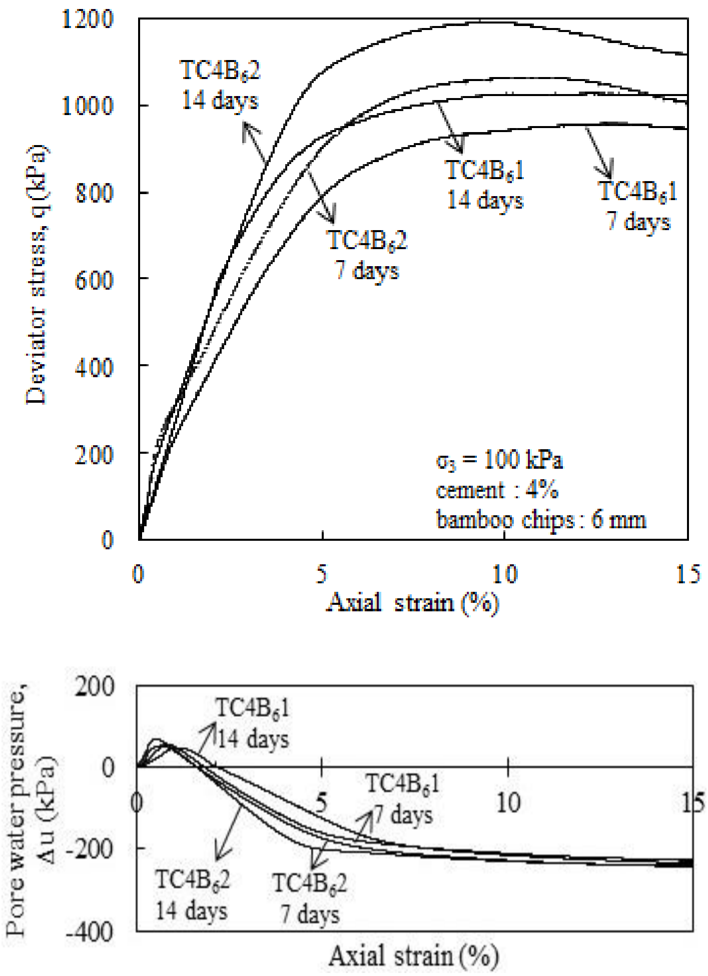


Figure 3.11. Comparison of stress-strain relationship and pore water pressure in variation of curing time (6 mm bamboo chips).

Different performance is shown by 10 mm bamboo chips addition. The characteristic of each mixture can be clearly analyzed using the relationship between axial strain and deviator stress in Fig. 3.12. It is because the curves coincide each other in stress path. So, it is difficult to distinguish. It can be seen that specimen cured for 7 days and 14 days show similar curve with Curve 4 and Curve 3 in Fig. 3.1(b), respectively. It can be concluded that mixture still behaved in hardening model for 7 days curing time. But, after 14 days curing time, the mixture changed to behave into softening model. It may be because the ability of 10 mm bamboo chips in absorbing water prevents cement to react more with water. High water absorbability is important properties of bamboo material as the additional material in the mixture, but it also requires the consideration regarding the cementation reaction.

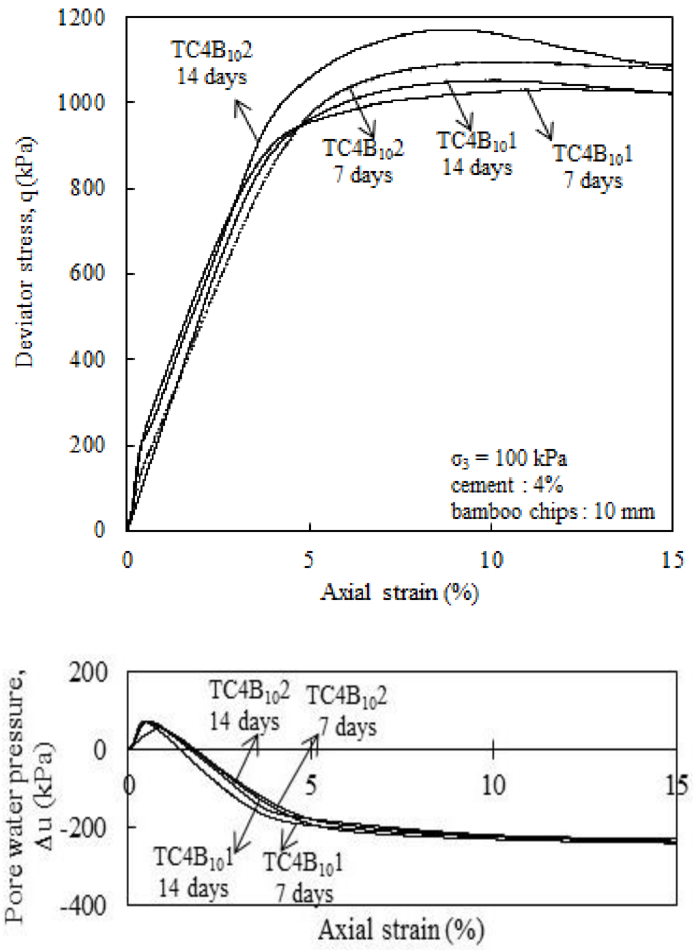


Figure 3.12. Comparison of stress-strain relationship and pore water pressure in variation of curing time (10 mm bamboo chips).

Effect of Cement Addition

Variation of cement content is shown in Fig. 3.13. It shows that cement addition provides higher result compared to the utilization of bamboo chips only. This can be concluded that bamboo chips are not suitable as a substitute of cement material. In addition, compared to the failure line cemented sand soil (TC4), bamboo chips in non-cemented mixture lies below that line. It shows that cement addition is required in this method. In addition, compared to the stress path of TC4, 1% addition of 6 mm bamboo chips provides similar characteristic.

However, addition of bamboo chips improves the strength of cemented sand. This statement is approved by the comparison of results that can be seen in Fig. 3.14. This figure provides information regarding the increment of q_{max} in 4% cement content. The increment was calculated by comparing the increasing q_{max} due to additional bamboo chips to the cemented sand soil (without bamboo chips addition) at the same curing time period. It shows that the higher content of bamboo chips, the higher strength of the cemented sand. In this figure, it is also shown that 6 mm bamboo chips are able to increase strength more than 10 mm bamboo chips.

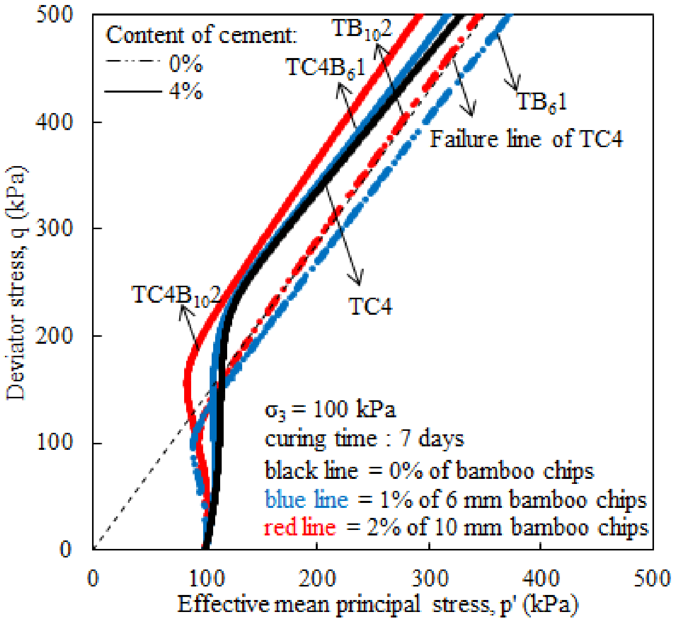


Figure 3.13. Stress path in variation of cement.

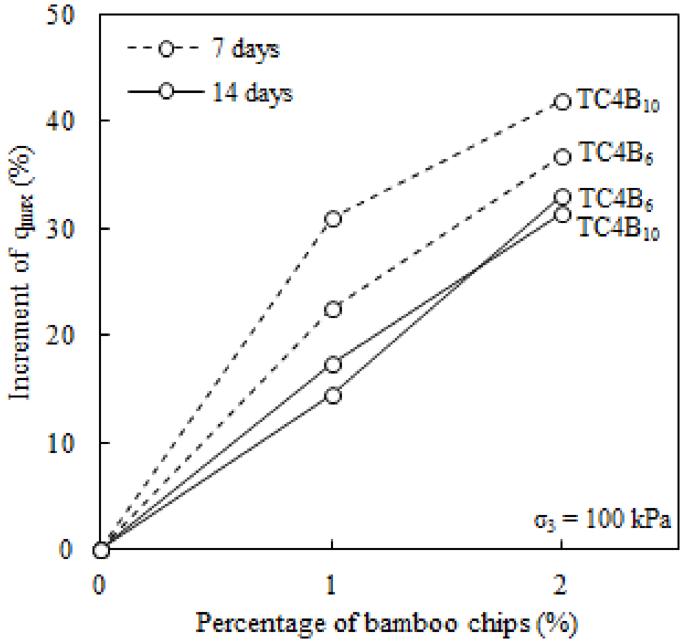


Figure 3.14. Increment of q_{max} compared to the cemented sand soil at the same curing time period.

Based on the result of dilative behavior investigation and comparison among increasing strength of mixtures as the result of undrained monotonic triaxial compression tests, 6 mm bamboo chip showed optimum improvement in the cemented sandy soil. This conclusion is in the line with the previous results, i.e. physical characteristic by elongation-flatness ratio and water absorbability in the previous chapter, as well as coefficient of permeability in this chapter.

3.6 Conclusions

Investigation of bamboo chips effect to the permeability and dilative behavior of cemented sandy soil was highlighted. The negative tendency to the permeability and dilative behavior was shown by bamboo chips-sandy soil mixture compared to cemented sandy soil. Conversely, the addition of bamboo chips in cemented sandy soil provides positive tendency. It can be concluded that bamboo chips is reliable as the reinforcement material in cemented sandy soil instead of cement replacement. Furthermore, 6 mm bamboo chips provided optimum result on the improvement of permeability and dilative behavior compared to 10 mm bamboo chips. This conclusion was utilized for further investigation in the next chapter.

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CHAPTER 4

EFFECT OF BAMBOO LEAF ASH ADDITION IN CEMENTED BAMBOO CHIPS-SANDY SOIL MIXTURE ON CHEMICAL, MECHANICAL PROPERTIES, LIQUEFACTION RESISTANCE, AND ENVIRONMENTAL IMPACT

4.1 Introduction

Effect of bamboo leaf ash (BLAsh) utilization in improvement of cemented bamboo chips-sandy soil was discussed in this chapter. This chapter utilized conclusion from previous chapter regarding the optimum content and type of bamboo chips. Furthermore, optimum content of BLAsh was recommended to perform the proposed mixture design.

4.2 Literature review

4.2.1 Potential of bamboo leaf

In general applications, most part of bamboo used is bamboo culm, whereas the utilization of bamboo leaf is still not maintained well. In Japan and Indonesia, bamboo leaf is unused, only used as a natural fertilizer, or burned in open area. On the other hand, bamboo leaf utilization is also explained in Chapter 1 that can be seen in Fig. 1.9. In the figure, bamboo leaf is shown can be utilized as bamboo drink, medicine, pigment, and bamboo juice. It informs that this material can be utilized using modern machine to produce the products. Otherwise, bamboo leaf is a waste material with low value. Figure 4.1 shows the abundance of bamboo leaf as unutilized material. It is also the problem of some countries that have high potential of bamboo resources and require recycling as one of the solutions to agricultural wastes, i.e. Brazil, Nigeria, and India. It is shown by the presence of several researches which developed the utilization of bamboo leaf in these countries (Dwivedi et al., 2006; Singh et al., 2007; Frias et al., 2012; Villar-Cocina et al., 2011; and Asha et al., 2014). In the form of BLAsh, some studies investigated its utilization as alternative material with high availability, low processing cost and ease of handling with little or no equipment and skill requirements to replace cement (Utodio et al., 2015).

Figure 4.1. Unutilized bamboo leaves in bamboo forest. Photos were taken in bamboo forest in Yogyakarta, Indonesia.

4.2.2 Bamboo leaf ash as cement replacement

Investigation to the chemical and mineral characteristic is required to determine whether a material has pozzolanic characteristic as the requirement to replace cement. Investigation to the chemical content defines the important compound of pozzolanic material, i.e. silica and/or alumina. This content has ability to hydrate with calcium hydroxide in the chemically reaction. This process results cementing properties. Utilization of natural pozzoalanic material in cement replacement has widely developed (Chmeisse, 1992).

The amount of SO_3 and the total amount of SiO_2, Al_2O_3, and Fe_2O_3 describe the chemical requirements of the pozzolans. ASTM C618–03 mentioned the minimum amount of SiO_2, Al_2O_3, and Fe_2O_3 is 50% for class C and 70% for class N and F pozzolans, whereas the maximum amount of SO_3 is 4% for class N and 5% for class F and C pozzolans. Class N is raw or calcined natural pozzolan, class F is pozzolanic fly ash from burning anthracite or bituminous coal, whereas class C is pozzolanic and cementitious fly ash from burning lignite or bituminous coal.

Dwivedi et al. (2006), Singh et al. (2007), Frias et al. (2012), Villar-Cocina et al. (2011), and Asha et al. (2014) investigated the characterization and determination of pozzolanic content of BLAsh. Chemical content of BLAsh resulted by previous researchers was summarized in Table 4.1. Based on Table 4.1, this result shows that BLAsh is classified as class N pozzolan by low content of SO_3 and high total amount of SiO_2, Al_2O_3, and Fe_2O_3. T. By X-ray fluorescence (XRF) test, Villar-Cocina et al. (2011) conducted mineralogical study. Based on the result (Fig. 4.2), BLAsh has high amorphous nature shown by the broad band localized 20-30^o 2θ. Crystalline materials were not detected. The characteristic shown is similar with characteristic of silica fume. Based on Siddique and Khan (2011), silica fume is a byproduct of silicon and ferro-silicon industry. This material is widely used as a pozzolanic admixture by its ability to increase mechanical properties of concrete.

Table 4.1. Summary of BLASh Chemical Content by Previous Studies

Country - Author	Chemical content (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	SO_3
India									
Dwivedi, et.al. (2006) Singh, et. al. (2007) Amu and Adetuberu (2010)	75.9	4.13	1.22	7.47	1.85	5.62	0.21	0.20	1.06
Brazil									
Villar-Cocina, et.al. (2011)	80.4	1.22	0.71	5.06	0.99	1.33	0.08	-	1.07
Frias, et.al. (2012)	78.71	1.01	0.54	7.82	1.83	3.78	0.05	0.08	1.00
Nigeria									
Umoh and Odesola (2015)	72.25	4.08	1.97	4.23	1.01	3.15	-	0.35	0.15
Dada and Faluyi (2015)	74.9	5.13	1.22	9.47	1.85	3.62	0.21	0.20	1.06

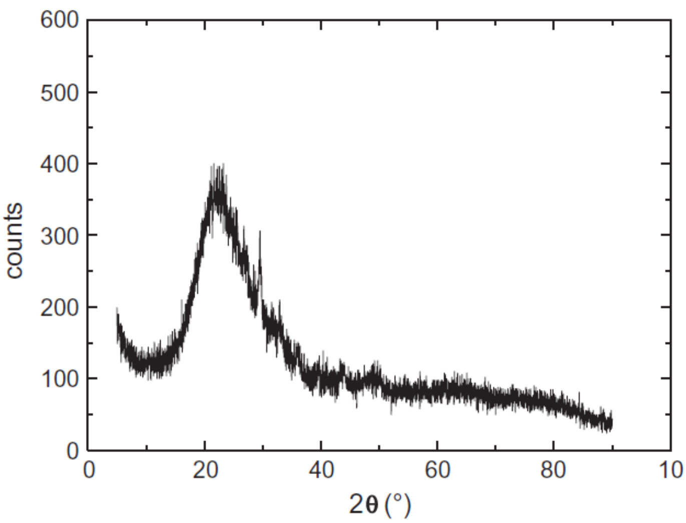


Figure 4.2. XRD pattern of bamboo leaf ash (BLAsh) (Villar-Cocina et al., 2011).

In order to investigate the pozzolanic activity of BLAsh, Frias et al. (2012) conducted determination of fixed lime percentages in relation with the total content of calcium hydroxide up to 90 days of time. Result of the determination is shown in Fig. 4.3. By the result, it was shown that BLAsh has very high reactivity. BLAsh showed high activity even after 24 h of reaction that reached 82% of total lime content in solution. In addition, after 3 days, BLAsh reached 90%. This value was then constant after 3 days. It was concluded that the pozzolanic reactivity has been finished. Thus, by some considerations above, BLAsh was concluded that it has ability to replace cement material due to its high pozzolanic characteristic.

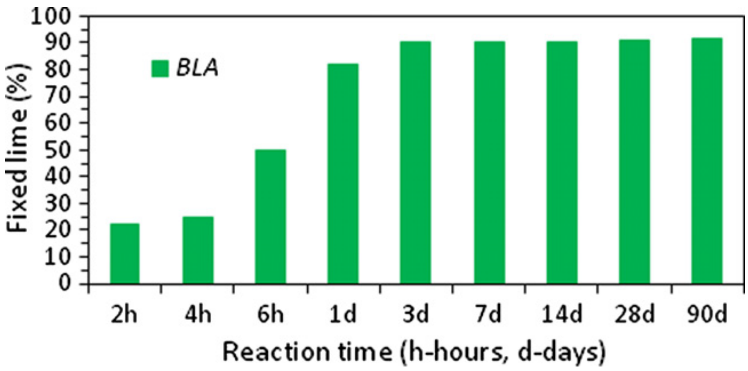


Figure 4.3. Evaluation of fixed lime in BLAsh/$Ca(OH)_2$ system (Frias et al., 2012).

4.2.3 Utilization of bamboo leaf ash

BLAsh has been proved able to be partial replacement in some applications. In application of structure engineering, there were some studies that conducted investigation of cement replacement by BLAsh. In cement paste and mortar, Umoh and Odesola (2015) recommended 15% cement replacement by BLAsh as the optimum mixture by the high strength of mortar. They also explained that BLAsh addition also affects the water absorption and apparent porosity of mortar. In concrete application, Asha et al. (2014) concluded that 10% cement replacement by BLAsh was favorable mixture design by high compressive strength and optimum durability. Whereas Umoh and Femi (2013) investigated effect of BLAsh utilization combined with periwinkle shell ash in concrete. They conducted test of compressive and tensile strength, water absorption, porosity, and bulk density. Based on the results, they concluded that 20% cement replacement by BLAsh was the optimum mixture. This mixture provided higher compressive and tensile strength and lower water absorption and porosity compared to original concrete without BLAsh. In Nigeria, lateritic soil is very abundant. However, its utilization is limited due to its low strength. In order to suggest the utilization of this type of soil in structure application, Utodio et al. (2015) developed study to improve lateritic soil utilization as walling material by using combination with BLAsh addition. They investigated effect of BLAsh on compressive strength, moisture absorption resistance, and the abrasion resistance. Based on their study, mixture design was suggested based on the purpose of application. For load bearing outer walls, 5% and 10% were the optimum content of BLAsh in replacing cement. For non-load bearing indoor walls, 20% and 25% cement replacement by BLAsh were recommended. Whereas 15% BLAsh content in replacing cement also could be applied for non-load bearing outer walls.

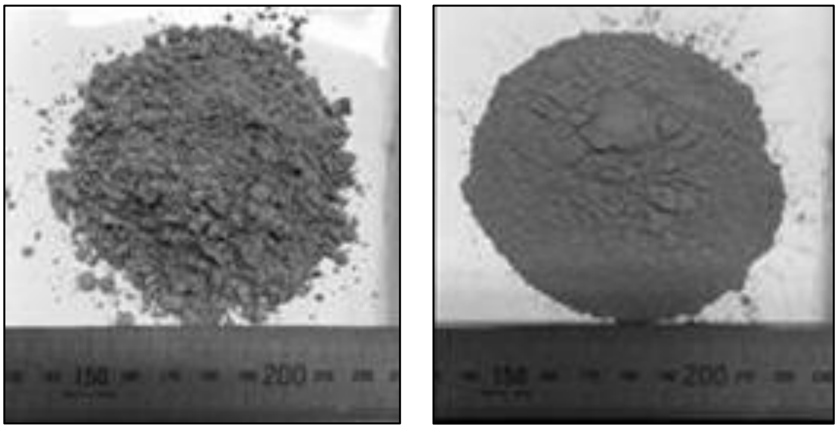
In geotechnical study, there were limited studies investigating the utilization of BLAsh. Some of researchers are Iorliam et al. (2013); Amu and Babajide (2011); Amu and Adetuberu (2010); and Dada and Faluyi (2015). Focus on improvement of shale soil for road structure, Iorliam et al. (2013) conducted tests of particle size distribution, Atterberg limits, compaction, unconfined compressive strength (UCS), California Bearing Ratio (CBR), and durability. Based on the result, BLAsh addition showed the improvement of index plasticity, UCS, and CBR. However, BLAsh addition in shale soil improvement did not satisfy the requirement of road structure material. Hence, they suggested for utilizing BLAsh as modifier with the addition of cement, lime, or other additives material. On the other hand, Amu and Babajide (2011); Amu and Adetuberu (2010); and Dada and Faluyi (2015) investigated the effect of BLAsh on stabilization of lateritic soil in highway construction. Amu and Babajide (2011) concluded that BLAsh has potential on the improvement of lateritic soil, whereas Amu and Adetuberu (2010); and Dada and Faluyi (2015) focused on utilization of BLAsh and lime combination in lateritic soil improvement. As an inorganic soil which has high index plasticity and thus potential of expansive soil, BLAsh addition proved that has ability in improving the properties combined without and with lime. Based on the references above, development of BLAsh utilization in geotechnical application was required.

4.3 Research objectives

Objective of this chapter is to determine the effect of BLAsh utilization as partially cement replacement in cemented bamboo chips-sandy soil mixture on chemical, mechanical, liquefaction resistance, and environmental impact. Based on the results, optimum content of BLAsh is defined to be proposed in reducing cement content in mixture.

4.4 Methodology

In this study, there are two types of pozzolanic materials used, i.e. BLash and Portland cement, shown in Fig. 4.4(a) and 4.4(b), respectively. Same as the previous chapters, cement used in the study was Ordinary Portland Cement (OPC).



(a) (b)

Figure 4.4. (a) BLAsh and (b) Portland cement.

Bamboo leaf waste was obtained from Nouken Sangyou Co. Ltd. BLAsh was produced in Geotechnical Laboratory, Kyushu University. Dry bamboo leaf was burnt in an open air, stopped after it becomes black in color, and then heated in furnace at 600˚C for 2 hours to produce bamboo leaf in grey in color. Once heated, it was cooled and grinded using mortar and pestle, then sieved using 75 μm mesh wire. The BLAsh is made in the constant temperature (about 20ºC). The most important of the making process of the BLAsh is the storage after finish the process. It must be kept in the closed storage to avoid the agglomeration by air or water. BLAsh is produced about 10% to dry mass of dried bamboo leaf. Based on Umoh and Odesola (2015), specific gravity (G_s) of BLAsh is 2.64, whereas Portland cement is 3.10.

To investigate chemical content of each pozzolanic material, Energy Dispersive X-ray (EDX) was conducted. The test utilized SEM super scan SS-550 apparatus (Fig. 2.10). Based on Essential Knowledge Briefings (EKB) (2015), EDX test can ideally be utilized as easy technique to determine the elements and chemical compounds in specimen. By delivering high energy electrons in an electron microscope to the sample, information about elemental composition is defined using X-ray mapping on the magnified image of the sample. Concentration of chemical compounds can be analyzed easily because the information is provided in percentage of mass or atomic fraction. However, geometric condition and preparation of sample are important issue in practical of the test. The accuracy of result can be achieved by reducing the deviation. Ideal linear absorption path is achieved by flat and homogenous sample. In addition, the sample must be clean from minerals, polymers, metal, and ceramics (Miler and Mirtic, 2013). By this reason, determination of chemical compound in this study preferably was applied on homogenous material such as cement and BLAsh than the mixtures. This result is expected to determine initial condition of mixture due to cement and/or BLAsh addition. Observation was conducted by calculating CaO/SiO_2 ratio as an important indicator of improvement by pozzolanic material. Generally, the higher ratio performs the higher improvement. However, the variation of CaO and SiO_2 availability in pozzolanic material performs different tendency (Tastan et al., 2011). The ratio was obtained based on the percentage analysis by weight of combination between cement and BLAsh. The percentage variation of each material is shown in Table 4.2.

Besides chemical analysis, mechanical properties of mixtures containing Toyoura sand, water, bamboo chips, cement, and BLAsh was investigated by conducting static triaxial test. Same as the explanation of specimen and the preparation in the previous chapters, the dimensions of specimen are 50 mm diameter and 100 mm height in cylinder. The mixture variation in this chapter is presented in Table 4.2. This chapter followed the conclusion of previous chapter about determination of optimum type of bamboo chips in mixture. BLAsh content was varied in the mixtures using 2% of 6 mm bamboo chips as constant type and content of bamboo chips. In addition, percentage of total pozzolanic material is also kept constantly in the amount of 2%. The definition of total pozzolanic material is the total amount of cement and BLAsh in the mixture. Water addition of 20% was decided based on the preliminary trial considering the workability reason. The percentages of water and pozzolan referenced to dry mass of Toyoura sand, whereas percentage of BLAsh are referenced to total pozzolanic material. Specimen was prepared by mixing all materials in dry condition into homogeneous color mixture then pour water into the mixture. Compaction was conducted in acrylic cylinder. After curing, acrylic cylinder was removed.

Table 4.2. Specimen Variations

Total pozzolan (%)*	Ratio by total pozzolan			Bamboo chips (%)*	Mixture code
	BLAsh	:	Portland cement		
2	0	:	1	2	$TC_{100}BL_0$
	1	:	3		$TC_{75}BL_{25}$
	1	:	1		$TC_{50}BL_{50}$
	3	:	1		$TC_{25}BL_{75}$
	1	:	0		TC_0BL_{100}

Notes:

*The percentages are referenced by dry weight of Toyoura sand

Same as the previous chapters, undrained static triaxial test utilized consolidated-undrained method with the pore water pressure measurement during loading (ASTM D 4767-11). In addition, undrained cyclic triaxial test was conducted to determine the liquefaction resistance due to BLAsh addition. Sine wave was controlled with 0.1 Hz of frequency. Same as above, specimen was observed with more than 0.9 of B-value after saturation process. In this study, liquefaction failure was defined as the point at initial liquefaction or at limiting cyclic strain amplitude. It was shown by maximum excess pore water pressure required in order to reach 95% of effective confining stress otherwise, 5% of double amplitude (DA) of cyclic axial strain was achieved. Single amplitude of cyclic shear stress (σ_d) was varied based on the condition of each specimen. Based on variation of σ_d, variation of cyclic stress ratio (CSR) as a normalized cyclic shear stress by the initial effective overburden pressure was also performed to provide trend of liquefaction resistance. In cyclic triaxial test, CSR is defined as $\sigma_d/2\sigma'_3$.

Figure 4.5. Cyclic triaxial test apparatus.

In determining the environmental impact of BLAsh utilization in the cemented bamboo chips-sandy soil, effluent water that flows from the system/mixture is prepared. There are two methods in preparation of leachate water, i.e. water/batch leaching test and column leaching test. Sauer et al. (2012) suggested that column leaching method is more reliable in environmental assessment of soil improvement. The laminar flow in column leaching method closes field conditions. By this reason, this study also utilizes column leaching method to investigate the effect of BLAsh addition in cemented bamboo chips-sand soil to the water that flows through the mixture. The investigation was conducted by measurement of pH value and heavy metal content of the leachate water.

Leaching column test was implemented following ASTM D 4874. After curing time, specimen was prepared in the leaching column to allow saturation process using distilled water. Low pressure (less than 0.8 kg/cm^2) was used to perform high degree of saturation. Water flows in an up-flow mode. To approach field condition, hydraulic gradient was kept less than 1. Effluent water was collected by sealed cylinder with vacuum pressure to avoid air trap. Leaching column test is depicted in Fig. 4.6. In this study, effluent water used in analysis is the result of completed 1, 2, 4, and 8 pore volumes. One pore volume is approached by 24 hours after flowing water to the specimen. Effluent water tested was about 50 ml for each specimen that can be seen in Fig. 4.7. Sample water was filtered using 0.22 µm filter paper (Fig. 4.8), then tested to analyze 7 heavy metals content, i.e. Cadmium (Cd), Chromium (Cr), Lead (Pb), Magnesium (Mg), Iron (Fe), Zinc (Zn), and Copper (Cu), by Atomic Absorption Spectrometer (AAS) using ANA-182 in Geotechnical Laboratory, Kyushu University (Fig. 4.10). Standard liquids for each heavy metal were prepared in 7 concentration variations (0.5; 1; 2; 4; 5; 10; and 20 mg/L) to obtain the calibration line. Besides heavy metal content, leachate water was utilized to determine the pH value to determine effect of BLAsh addition in alkalinity characteristic (Fig. 4.9).

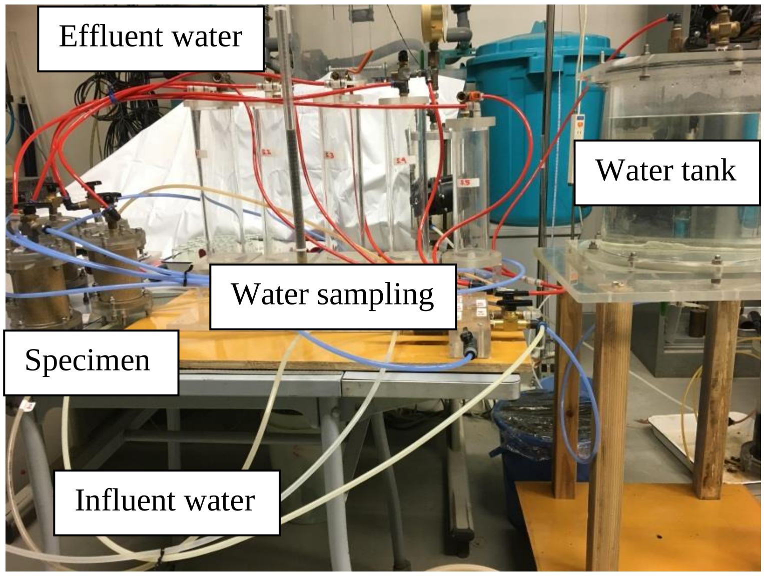


Figure 4.6. Leaching column test.

Figure 4.7. Effluent water.

Figure 4.8. Apparatus of effluent water filter.

Figure 4.9. Apparatus of pH value measurement.

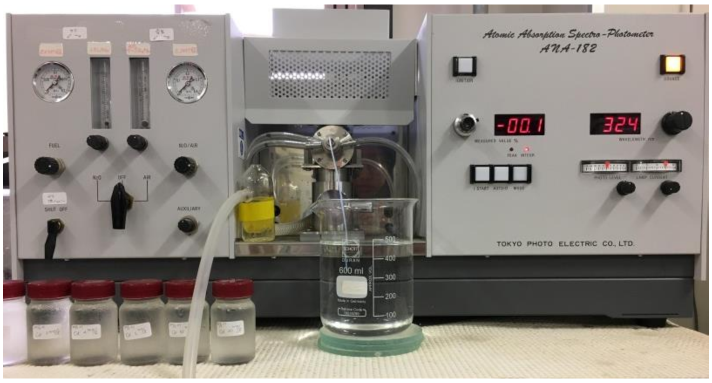


Figure 4.10. Atomic Absorption Spectrometer (AAS) apparatus.

4.5 Results and discussions

4.5.1 Chemical compound

Based on the EDX test, chemical compound of cement and BLAsh used in this study was summarized in Table 4.3. As explained above, this result is in line with the classification of BLAsh as pozzolan material class N due to content of SO_3 and total amount of SiO_2, Fe_2O_3, and Al_2O_3. In addition, it can be seen that dominant content of cement is CaO, whereas BLAsh has SiO_2 as the highest compound.

Tastan et al. (2011) and Talib et al. (2015) are two of some literatures that stated the general chemical reaction resulting cementitious and pozzolanic gels (Equations 4.1 and 4.2). Reaction between cement with H_2O results CSH (calcium silicate hydrates) and $Ca(OH)_2$ (calcium hydroxide). Furthermore, if pozzolanic material is added, $Ca(OH)_2$ is able to react more to result CSH and/or CASH (calcium aluminate silicate hydrate gel). The CSH and CASH have adhesive characteristic that are able to bind particles and harden the mixture. Thus, the additional pozzolanic material provides improvement of cement hydration commonly referred as secondary pozzolanic reaction.

Table 4.3. Chemical Composition of BLAsh and Portland Cement by EDX Test

Elemental Oxide	Percentage by mass (%)	
	BLAsh	Portland Cement
CaO	6.00	65.03
SiO_2	78.29	19.72
Al_2O_3	1.21	2.06
Fe_2O_3	0.72	0.72
MgO	1.21	0.85
K_2O	5.03	0.63
Na_2O	-	-
SO_3	1.87	2.75
TiO_2	-	0.46
P_2O_5	-	4.90

CaO in cement + $H_2O \rightarrow$ CSH + **$Ca(OH)_2$** [4.1]

$Ca(OH)_2$ + SiO_2 in BLAsh + $H_2O \rightarrow$ CSH and/or CASH [4.2]

Papadakis (1999) reviewed that in the form of crystalline, Al_2O_3 and Fe_2O_3 are not reactive. However, Villar-Cocina et al. (2011) mentioned that crystalline minerals were not detected in the BLAsh. Thus, these contents also provide the improvement by its reactivity potential. But, CASH, as the reaction result of Al_2O_3 content shows long-term strength (Tastan et al., 2011), whereas this investigation focus on the short-term characteristic (7 days curing time). While for Fe_2O_3, the content in cement and BLAsh is relatively low compared to either CaO or SiO_2 content. Therefore, in this discussion, SiO_2 becomes the most indicative of increasing strength.

4.5.2 Static triaxial test

In order to investigate the effect of BLAsh ash as cement replacement and furthermore obtain the optimum content, variation of BLAsh was performed. The result of static triaxial test was shown by difference of maximum deviator stress ($\Delta q_{max} = q_{maxi} - q_{max0}$). Definition of q_{max} was explained in the previous chapters following ASTM 4767-11. Whereas definition of Δq_{max} is the difference between maximum deviator stress of mixture contains BLAsh (q_{maxi} = q_{max} of $TC_{75}BL_{25}$, $TC_{50}BL_{50}$, $TC_{25}BL_{75}$, and $TC_{0}BL_{100}$) and the mixture without BLAsh (q_{max0} = q_{max} of $TC_{100}BL_{0}$) at the same confining pressure (σ_3). Moreover, combination of SiO_2 and CaO content based on the percentage of cement and BLAsh in the mixture was also shown in the same graph (Fig. 4.11). Content of SiO_2 and CaO followed EDX test result in Table 4.3. This combination graph was utilized to explain the behavior of mixture strength under static loading based on the chemical consideration.

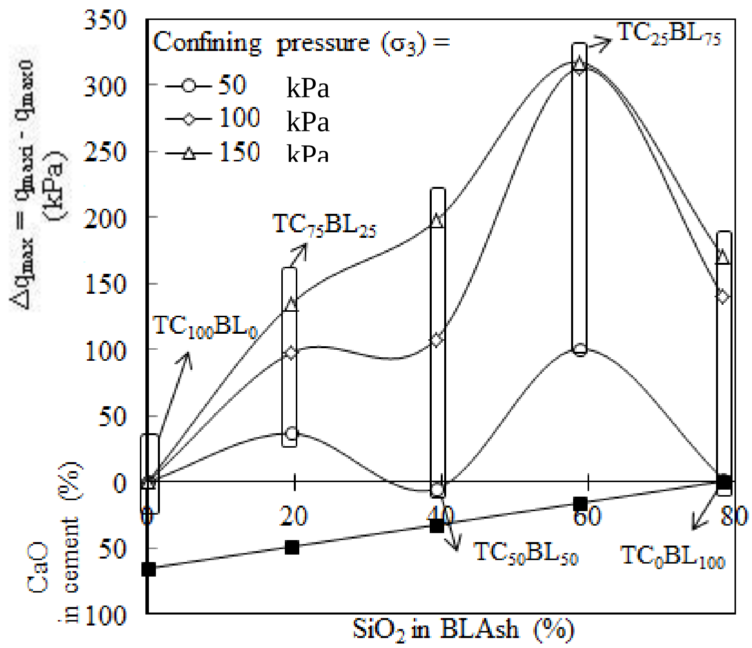


Figure 4.11. Result of static triaxial test to the variations of cement replacement by BLAsh.

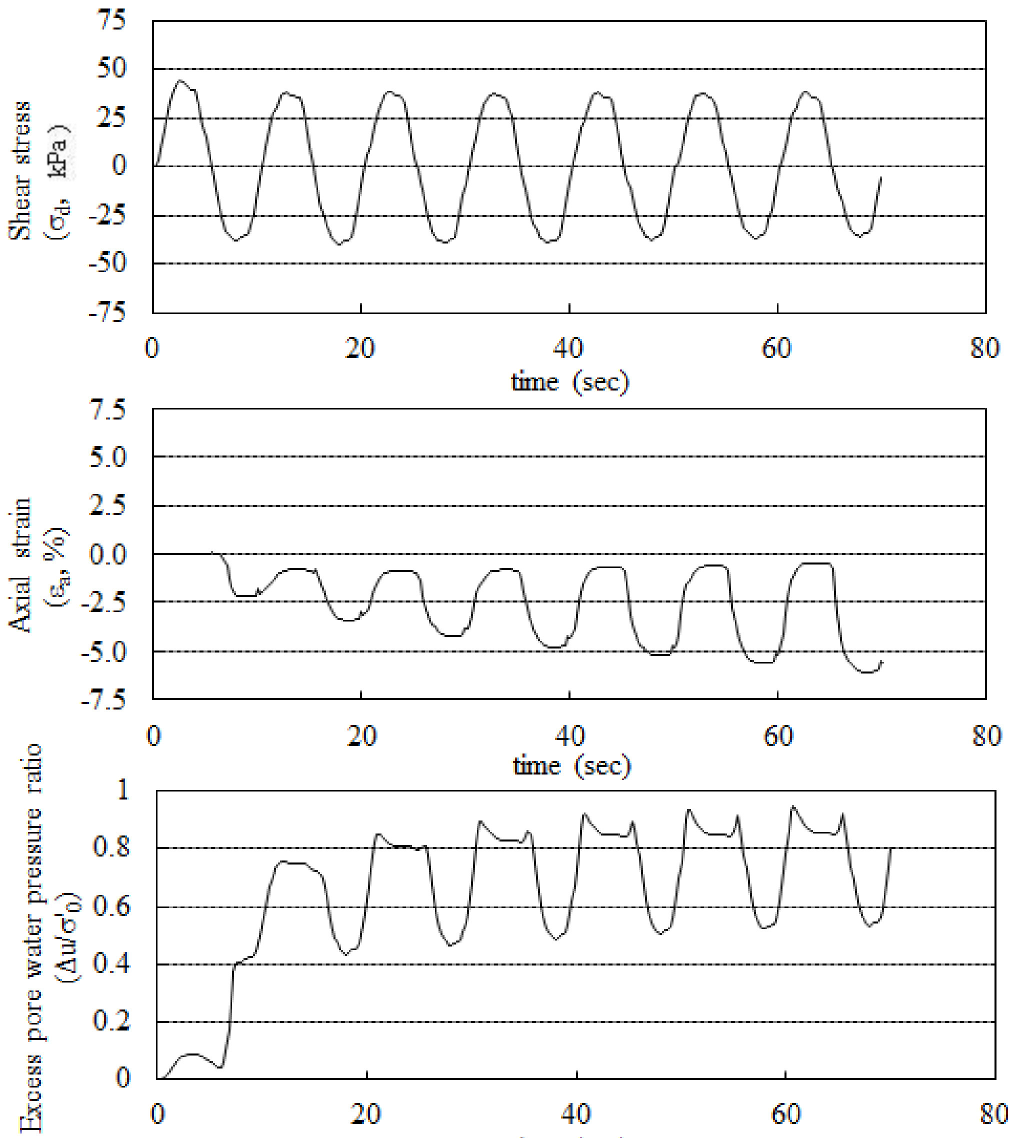
Based on the result of static triaxial test, the highest Δq_{max} was reached by mixture $TC_{25}BL_{75}$. Whereas, based on the combination of chemical content following percentage of cement and BLAsh, it can be seen Δq_{max} increases with the increasing SiO_2 content in BLAsh and decreasing CaO in cement simultaneously. However, there is peak point as the optimum value. It is because the lower CaO is not able to lead the $Ca(OH)_2$ as the result of oxidation between CaO and H_2O (Equation 4.1) and as the important reactant in secondary pozzolanic reaction by SiO_2 (Equation 4.2). The further indicator is shown by the optimum CaO/SiO_2 ratio. BLAsh itself has CaO content which also provides cementation reaction with water. This reaction is able to increase the secondary pozzolanic reaction without using amount of $Ca(OH)_2$ produced by cement. Based on this reason, CaO content in pozzolanic material also can be considered in the cement replacement activity (Marsh and Day, 1988). However, this study focused on the participation of each material in each reaction. It is also because amount of CaO and SiO_2 in BLAsh and cement, respectively, are relatively small compared to the SiO_2 and CaO in BLAsh and cement, respectively. Thus, it can be written that optimum value of Δq_{max} is reached by 58.72% SiO_2 in BLAsh and 16.26% CaO in cement. The CaO/SiO_2 ratio of the $TC_{75}BL_{25}$, $TC_{50}BL_{50}$, $TC_{25}BL_{75}$, and TC_0BL_{100} mixture are 2.49, 0.83, 0.28, and 0, respectively. It can be approved that 75% cement replacement by BLAsh is the optimum percentage to increase silica content and improve the strength of the mixture. The increasing strength is about 50% to the original mixture (without BLAsh content). Furthermore, the determination to conclude the optimum mixture by CaO/SiO_2 ratio is more appropriate. By this result, the ratio of about 0.28 is the optimum CaO/SiO_2 ratio in the partially replacement of cement by BLAsh material. Conversely, Talib (2015) mentioned that the higher ratio provides higher improvement. The higher ratio means the higher pozzolanic reaction mainly produced by CaO content of cement instead of secondary pozzolanic reaction produced by SiO_2 content of additional pozzoanic material. This current study clarifies that in the case of improvement using secondary pozzolanic reaction, SiO_2 content also takes the main part in improvement. Thus, peak curve is more reliable to determine the optimum ratio. This statement is approved by Nachbaur et al., (1997). They mentioned about two important steps in the cement hydration, i.e. coagulation and rigidification. In coagulation process, CSH was formed. The coagulation is clearly stronger at intermediate calcium (CaO) concentration. At the higher and lower content of calcium, the coagulation is still occurred but weaker. Also, Tastan

(2011) concluded the peak value as the optimum CaO/SiO_2 ratio of fly ash addition in organic soil stabilization. He stated that the optimum ratio of fly ash was between 0.5 and 1.0. This range is higher than the optimum ratio in this study. It may be due to the required pozzolanic reaction in the organic soil is higher than the poorly graded sandy soil. It can be concluded that the type of soil also affect the required CaO and SiO_2 in the mixture.

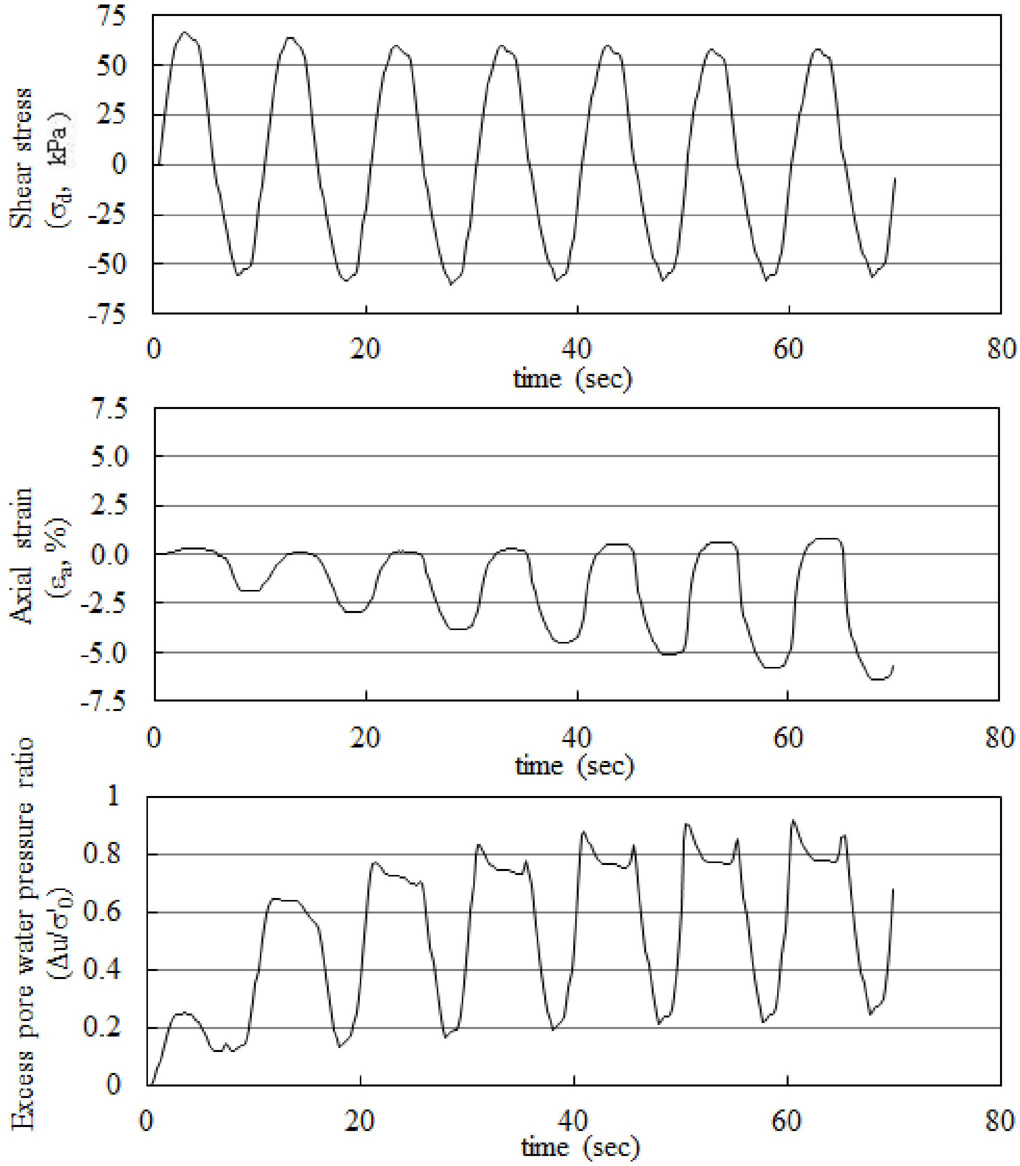
On the other hand, at the low confining pressure (σ_3 = 50kPa), 100% cement replacement by BLAsh (highest SiO_2 and lowest CaO) provides similar value with q_{max0}. It can be concluded that BLAsh is able to be totally cement replacement to reach same strength. Thus, it is in line with the explanation above that small amount addition of CaO in cement is able to increase strength to the peak point. In addition, effect of confining pressure was also shown. The higher confining pressure provides the higher Δq_{max} at the same content of CaO and SiO_2. Therefore, confining pressure may affect the interaction of particles in mixture.

4.5.3 Cyclic triaxial test

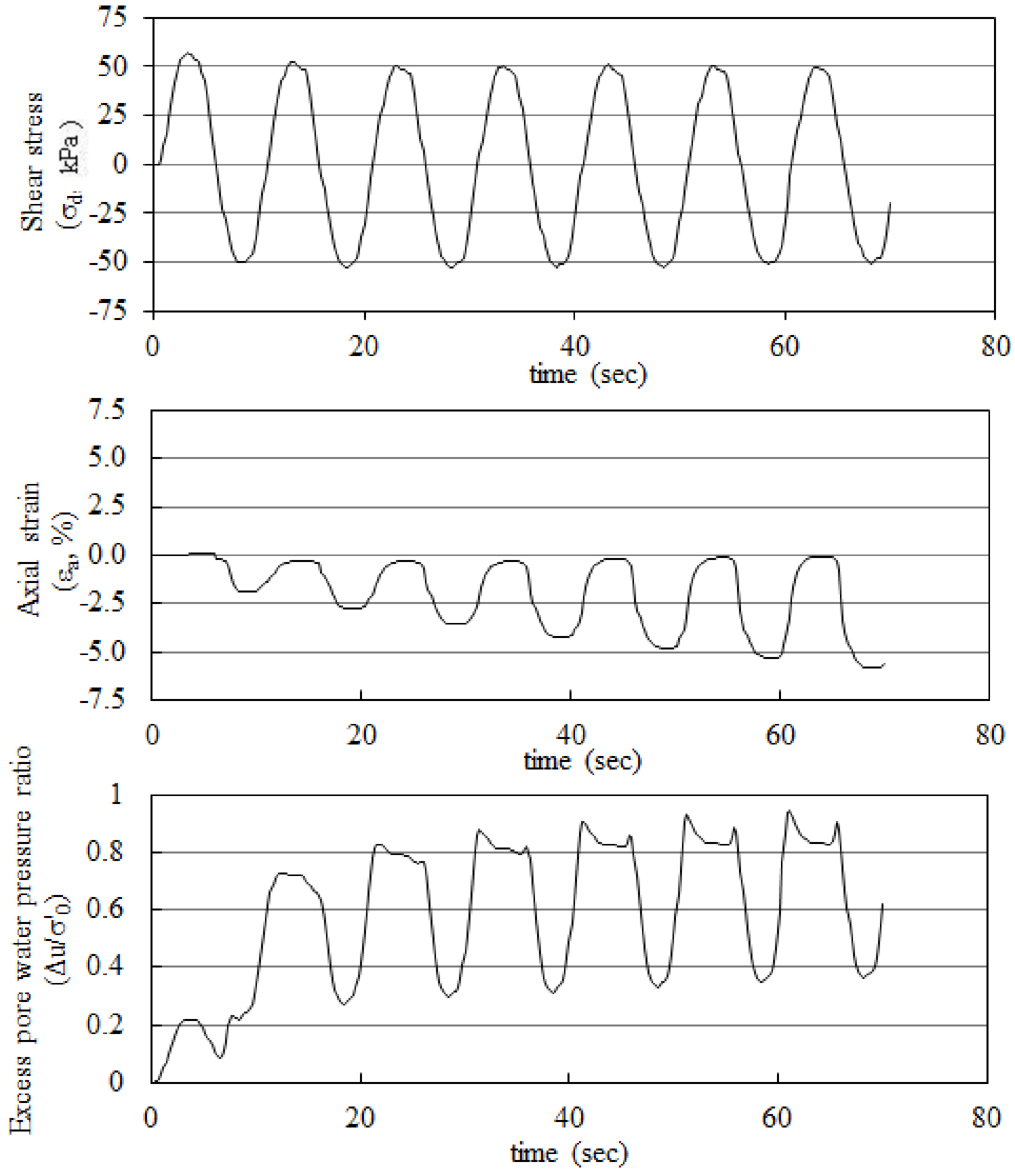
Based on the result of cyclic triaxial test, Fig. 4.12 shows the comparison among $TC_{100}BL_0$, $TC_{75}BL_{25}$, and $TC_{50}BL_{50}$ mixture which have similar number of cycles due to cyclic loading at 0.2, 0.3, and 0.25 CSR value, respectively. The different value of CSR shows the liquefaction resistance for each mixture. $TC_{100}BL_0$, $TC_{75}BL_{25}$, and $TC_{50}BL_{50}$ mixture reached 5% of axial strain for double amplitude (DA) as the initial liquefaction occurrence after 6, 5, and 6 cycles, respectively. $TC_{100}BL_0$ has lowest liquefaction resistance shown by lowest CSR at the similar number of cycles. It shows cement replacement by BLAsh material increases liquefaction resistance, especially 25% BLAsh content as the partially cement replacement. Liquefaction resistance also defines the density of soil or mixture. The higher liquefaction resistance informs the higher density. By this reason, 25% BLAsh content to replace cement increases the density. However, based on this result, decreasing liquefaction resistance is also shown by 50% BLAsh content in cement replacement. This mixture showed lower CSR value compared to $TC_{75}BL_{25}$ with the similar number of cycles. This decreasing liquefaction resistance is in line with the result of static triaxial test in previous discussion which 50% BLAsh in partially cement replacement showed negative effect in improving mixture strength.



(a)


Shear stress (σ_d, kPa)
75
50
25
0
-25
-50
-75
0
20
40
60
80
time (sec)
Axial strain (ε_a, %)
7.5
5.0
2.5
0.0
-2.5
-5.0
-7.5
0
20
40
60
80
time (sec)
Excess pore water pressure ratio ($\Delta u/\sigma'_0$)
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
time (sec)

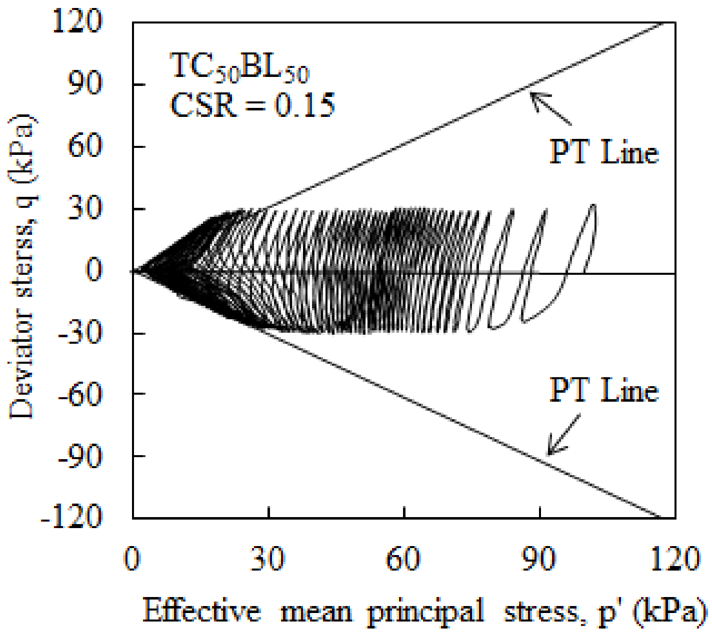
(b)



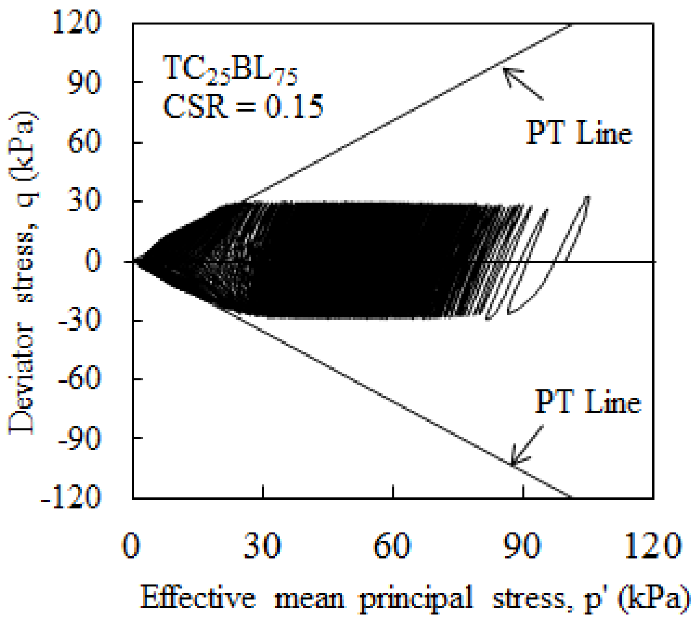
(c)

Figure 4.12. Results of cyclic triaxial tests of (a) $TC_{100}BL_0$ with CSR = 0.2, (b) $TC_{75}BL_{25}$ with CSR = 0.3, and (c) $TC_{50}BL_{50}$ with CSR = 0.25.

Furthermore, increasing liquefaction resistance is shown again by more addition of BLAsh, i.e. $TC_{25}BL_{75}$ mixture. This information is presented in effective stress path in Fig. 4.13. Failure due to liquefaction occurs when the effective stress reaches zero due to increasing pore water pressure. Thus, in effective stress path, if effective mean principal stress (p') equals zero, liquefaction is reached. In addition, phase transformation line (PT line) drawn in effective stress path based on the result of static triaxial test also can be utilized to indicate the initial of liquefaction shown by transition to contractive behavior (Konstadinou and Georgiannou, 2014). At the same CSR equals 0.15, $TC_{75}BL_{25}$ requires more number of cycles to reach PT line and p' of zero value compared to $TC_{50}BL_{50}$. This result also supports previous discussion regarding the highest improvement by 75% BLAsh as the partially cement replacement.



(a)



(b)

Figure 4.13. Comparison of effective stress path between $TC_{50}BL_{50}$ and $TC_{25}BL_{75}$ mixture at CSR = 0.15.

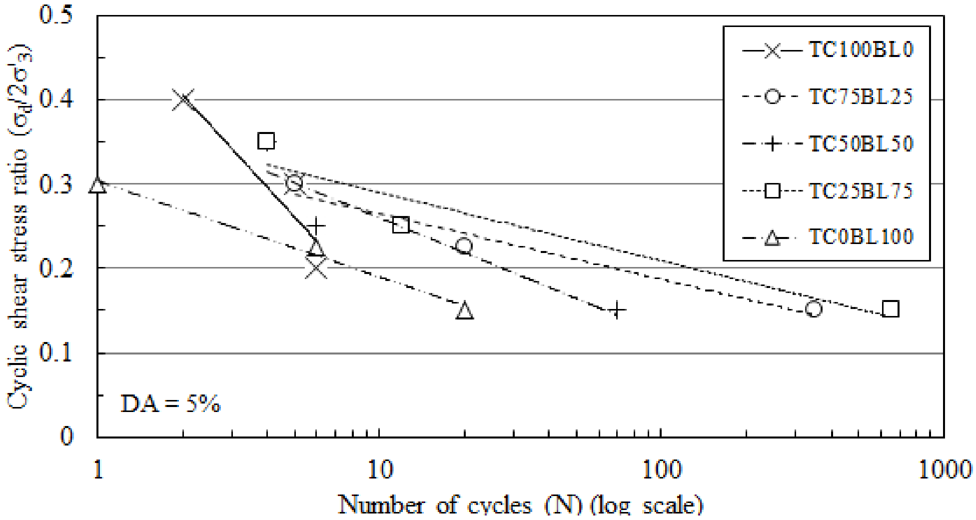


Figure 4.14. Comparison of liquefaction resistance based on the mixture variations.

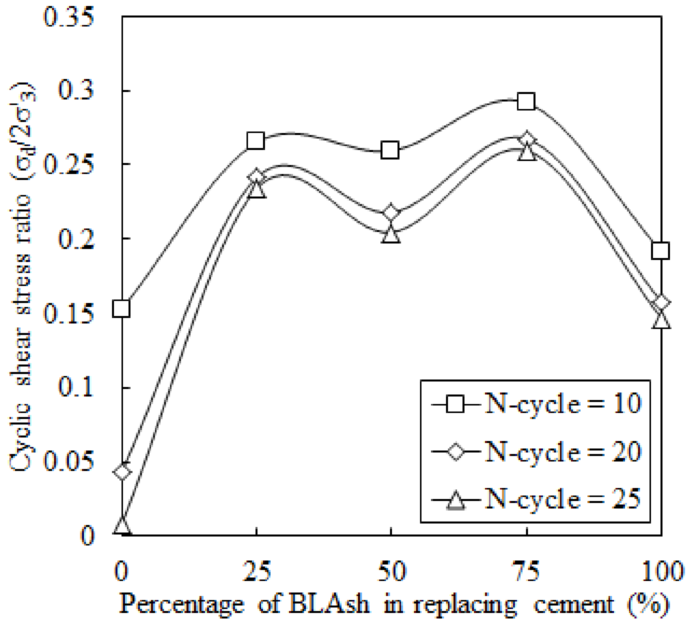


Figure 4.15. Comparison of CSR at the same N-cycle.

Other information was also shown by comparison among mixture variations based on the CSR variation that can be seen in Fig. 4.14. Based on this figure, liquefaction resistance for each mixture is shown clearly. At high CSR, i.e. more than CSR of 0.3, $TC_{100}BL_0$ showed higher point in the curve compared to other mixtures. The higher curve provides the higher liquefaction resistance. However, this condition has short consistency. Less than CSR of 0.3, $TC_{100}BL_0$ has low performance shown by steep curve. This mixture reaches liquefaction after 5 and 6 numbers of cycles at 0.3 and 0.2 CSR, respectively. Conversely, sloping curves are posed by improved mixtures by BLAsh addition. Using logarithmic regression equation of $TC_{100}BL_0$ curve defined as CSR = -0.158 ln (N) + 0.5163, extended curve can be predicted to conduct comparison of liquefaction resistance at the same number of cycles. Where, CSR is cyclic shear stress ratio and N is number of cycles. Figure 4.15 shows the comparison of CSR based on the constant N-cycle to determine more clearly the optimum mixture based on the liquefaction resistance. In this study, CSR_{20} corresponding to 20 cycles of loading is used as the comparison of liquefaction resistance. Compared to $TC_{100}BL_0$, cement replacement by BLAsh provides improvement of liquefaction resistance. $TC_{75}BL_{25}$, $TC_{50}BL_{50}$, $TC_{25}BL_{75}$, and TC_0BL_{100} increase 5.62, 5.07, 6.22, and 3.66

times of CSR_{20}, respectively. The highest improvement is shown by $TC_{25}BL_{75}$ mixture. This result also supports results of static triaxial test in the previous discussion.

4.5.4 Heavy metal content and pH measurement

Heavy metal content measurement is generally utilized to determine toxic contaminant or pollution in leachate water by material addition in soil improvement. Guidelines for drinking water quality published by government that provides allowable limit of heavy metal content was utilized to determine the safety of leachate water to environment (Goswani and Mahanta, 2006). This study utilized two systems of drinking water quality (Table 4.4), i.e. Japan Standard by Ministry of Health, Labor, and Welfare, Japan (2015) and Indonesia Standard by Ministry of Health, Indonesia (2010). Mostly, allowable limits are same between these two systems such as Cd, Cr, Fe, and Pb. However, Japan standard provides more stringent restriction for some heavy metal content such as Zn, Mg, and Cu.

Table 4.4. Guidelines for Drinking Water Quality (mg/L)

Metal	Standard	
	Japan	Indonesia
Cd	0.003	
Cr	0.05	
Fe	0.3	
Pb	0.01	
Zn	1	3
Mg	300 (hardness)	ND
Cu	1	2

Value of pH is defined as the negative logarithm of the hydrogen ion (H^+) concentration. The pH measurement is important to obtain information regarding acidity or alkalinity of a solution. The pH scale ranges from 0 to 14. Neutral solution is shown by 7 value of pH, whereas acidity and alkalinity solution are shown by less and more than 7 value of pH, respectively. Generally, cement material has high alkalinity shown by pH of 12 to 13. Its characteristic is required in mixture to provide the hydration and increased strength after due to reaction between cement and water (Grubb et al., 2007). In concrete, high alkalinity of cement is also required to avoid the corrosion occurs in acid environments. However, high alkalinity of cement causes environmental problem. It is harmful to human skin. There are some skin disorders due to highly frequency in contact with cement (Jen, 2014). In this study, the objective of partially cement replacement by BLAsh in bamboo chips-sand soil mixture decreases the environmental problem due to cement. Regarding the alkalinity, BLAsh addition was expected to neutralize the high alkaline soil mixture. In addition, the investigation to the relationship between pH value and the heavy metal content is also presented.

The measurements of pH value were presented as function of variations of BLAsh content as a partially cement replacement in the bamboo chips-sandy soil mixture and pore volume of flow shown in Fig. 4.16 and Fig. 4.17, respectively. The variation of pH of the mixtures varies between 8.11 and 11.53. Figure 4.16 shows that addition of BLAsh material decreases the pH value in variation of pore volume. The main reason is cement content reduction in the mixture along with the BLAsh addition. This result shows that BLAsh addition provides neutralization because pH value decreases approaching pH value of 7 as neutral condition. As mentioned above, cement has high alkalinity to provide hydration between CaO and H_2O. Thus, small value of pH in the cemented mixture is also not recommended to provide high strength due to cement hydration. Tremblay et.al. (2002) stated that the pozzolanic reaction is inhibited at the too low pH (< 9) in the soil-cement mixture. By this reason, it can be understood that totally cement replacement by BLAsh (TC_0BL_{100} mixture) decreases the strength which is shown in some test results in the previous chapter is caused by its too low pH value, i.e. 8.11. In Fig. 4.16, there is also information regarding small difference among pore volume variations. This information is explained in detail in Fig. 4.17. It shows that pH value of leachate water is constant along the period of water flow through the mixture.

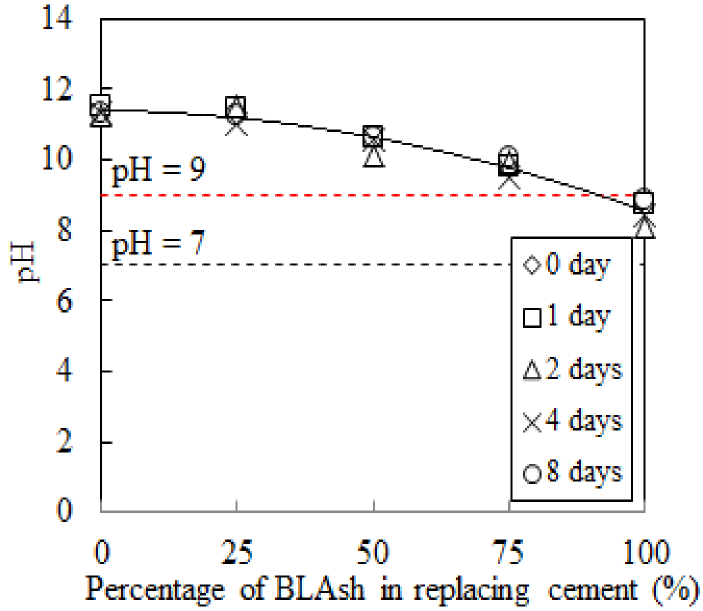


Figure 4.16. Result of pH measurement in variation of BLAsh percentage in partially cement replacement.

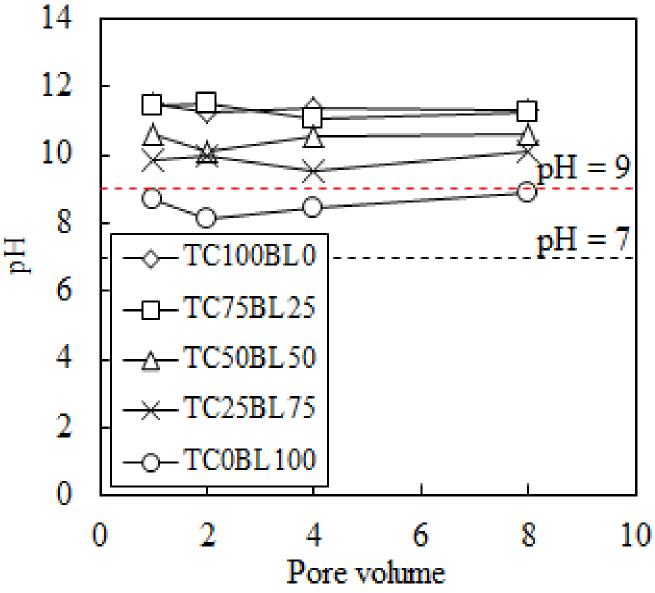
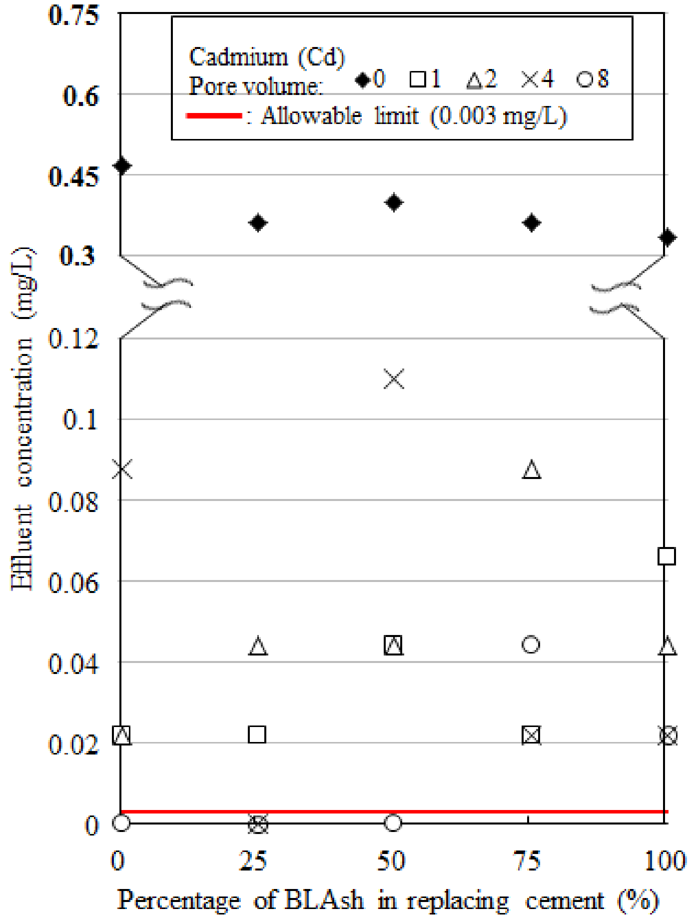
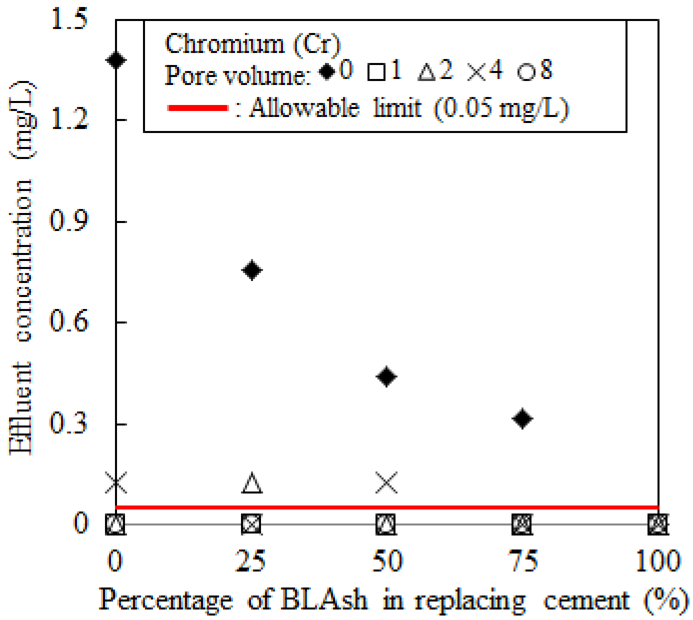


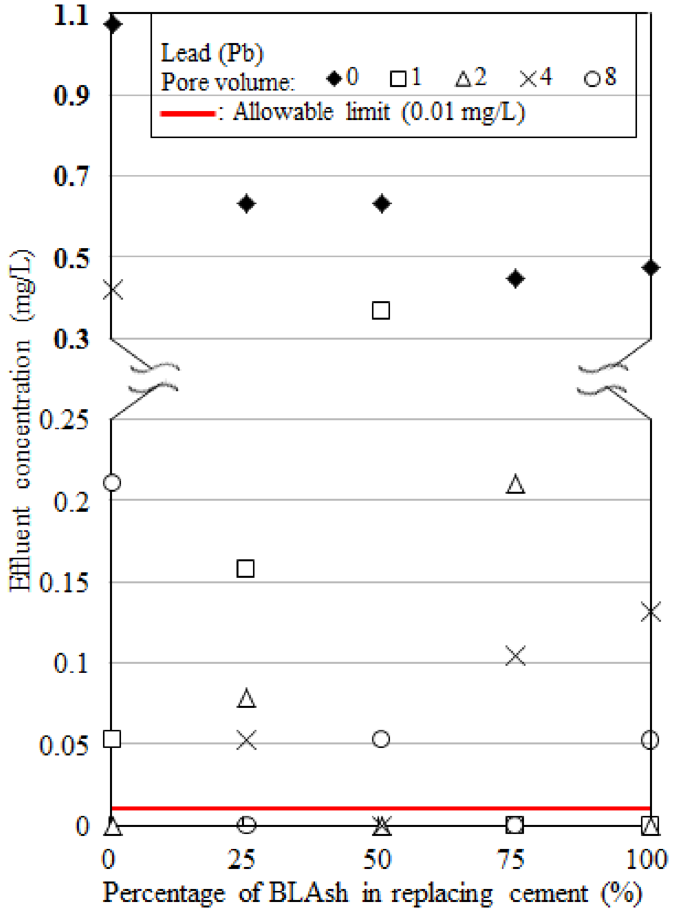
Figure 4.17. Variation of pH value in pore volume variations.


Cadmium (Cd)
Pore volume: ◆0 □1 △2 ×4 ○8
: Allowable limit (0.003 mg/L)
Effluent concentration (mg/L)
0.75
0.6
0.45
0.3
0.12
0.1
0.08
0.06
0.04
0.02
0
0
25
50
75
100
Percentage of BLAsh in replacing cement (%)

(a)

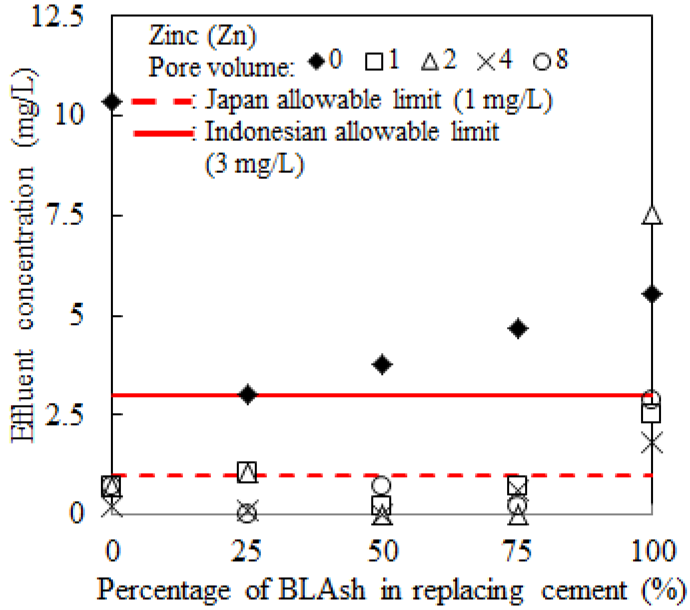

Chromium (Cr)
Pore volume: ◆0 □1 △2 ×4 ○8
: Allowable limit (0.05 mg/L)
Effluent concentration (mg/L)
1.5
1.2
0.9
0.6
0.3
0
0
25
50
75
100
Percentage of BLAsh in replacing cement (%)

(b)



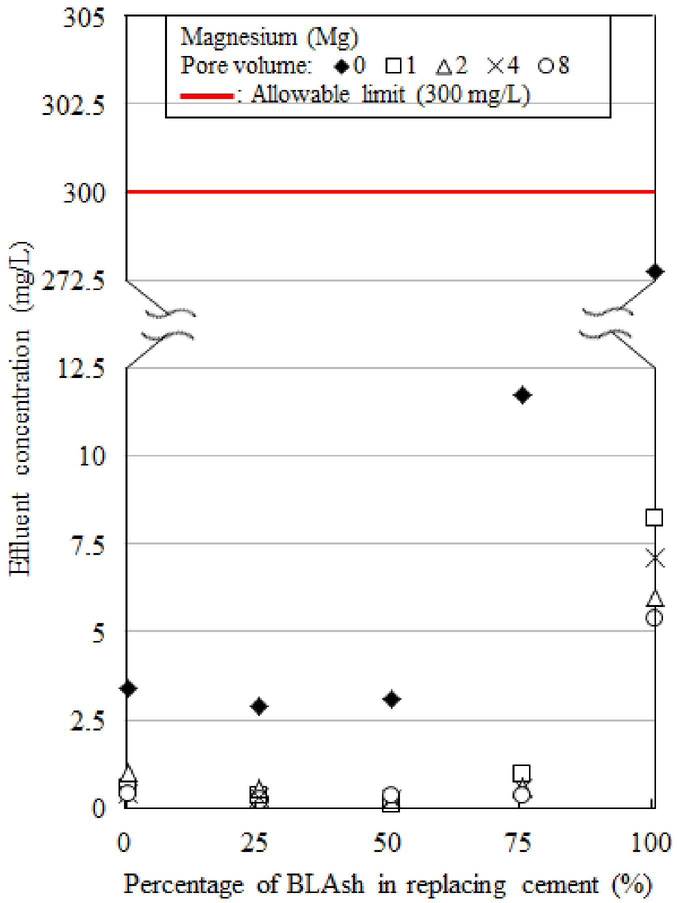
Lead (Pb)
Pore volume: ◆0 □1 △2 ×4 ○8
: Allowable limit (0.01 mg/L)
Effluent concentration (mg/L)
Percentage of BLAsh in replacing cement (%)

(c)

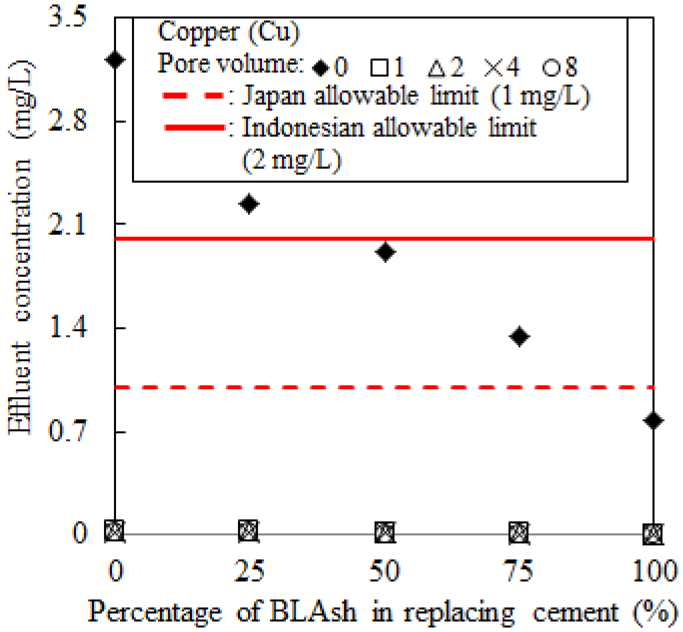


Zinc (Zn)
Pore volume: ◆0 □1 △2 ×4 ○8
: Japan allowable limit (1 mg/L)
: Indonesian allowable limit (3 mg/L)
Effluent concentration (mg/L)
Percentage of BLAsh in replacing cement (%)

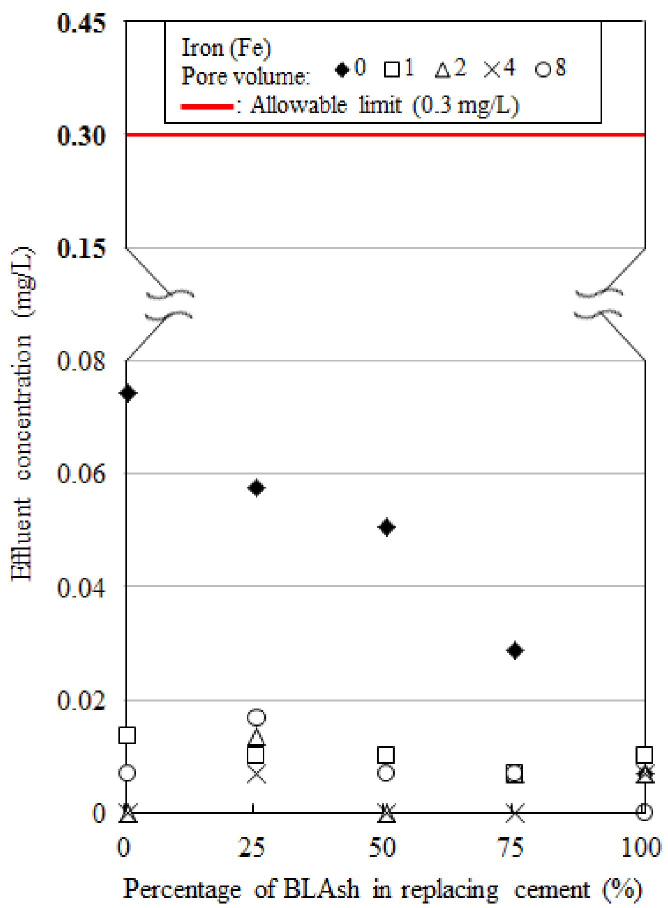
(d)


Magnesium (Mg)
Pore volume: ◆0 □1 △2 ×4 ○8
: Allowable limit (300 mg/L)
305
302.5
300
272.5
12.5
10
7.5
5
2.5
0
Effluent concentration (mg/L)
0
25
50
75
100
Percentage of BLAsh in replacing cement (%)

(e)


Copper (Cu)
Pore volume: ◆0 □1 △2 ×4 ○8
: Japan allowable limit (1 mg/L)
: Indonesian allowable limit (2 mg/L)
3.5
2.8
2.1
1.4
0.7
0
Effluent concentration (mg/L)
0
25
50
75
100
Percentage of BLAsh in replacing cement (%)

(f)



(g)

Figure 4.18. Content variation of (a) Cd, (b) Cr, (c) Pb, (d) Zn, (e) Mg, (f) Cu, and (g) Fe based on the variation of BLAsh percentage in replacing cement.

Based on the observation to the heavy metal content, Fig. 4.18 summarized the variations based on the BLAsh percentage in replacing cement and pore volume variations. These results show typical characteristic based on the type of chemical content. Mostly, heavy metal content decreases in the increasing BLAsh percentage. It can be concluded that BLAsh is able decrease the metal content in the mixture. However, negative effect was shown in Magnesium (Mg) content. At the 100% of cement replacement by BLAsh, Mg content in the 0 pore volume is 272.56 mg/L (the point is outside the graph). Regarding the relationship between heavy metal content and pH value, these results lead the conclusion that both parameters have strong interaction which is related to solubility Sauer et al.

(2012). Except Mg content, the high pH may lead the solubility of heavy metal. At the high pH, the heavy metal was eluted in high concentration. For Mg content, this result is in line with the fly ash addition in study result of Goswami and Mahanta (2006). The increasing Mg content may due to the additional ion by BLAsh.

In relation to the pore volume parameter, all heavy metal provides decreasing value along the pore volume (elapsed time). All heavy metal approaches zero content at 8 days. It can be approved that the continuously flowing water is able to wash the metal content in the mixture. In addition, it may be due to the ability of bamboo chips as organic matter in adsorption (Clare and Sherwood (1954). Definition of adsorption is the process in which atoms, ions or molecules from a substance.

In determining the appropriateness of the effluent water from the mixture to the environment, allowable limit was drawn in red line. Based on figures, it can be seen that in observation of Cd, Cr, Pb, and Zn content, all mixtures produce unsafe flowing water at the initial time due to its high content at 0 pore volume. It can be concluded that in the initial time after construction process, the management of flowing water through the mixture must be conducted. It has to be maintained, so that the effluent water will not flow to the water source. However, contents of Fe and Mg are always below the allowable limit. For Cu content, there is difference between allowable limit issued by Japan and Indonesian Government. Initial effluent water (at 0 pore volume) of 0% and 25% cement replacement by BLAsh are above the red line of Japan. Focus on the optimum mixture design, i.e. 75% cement replacement by BLAsh, the decreasing heavy metal contents are shown. In addition, all heavy metal contents after 8 days are lower than the allowable limit.

4.6 Conclusions

Effect of BLAsh utilization in cemented bamboo chips-sandy soil mixture was investigated. Investigations to determine chemical compound, mechanical properties, liquefaction resistance, and impact to the environment were conducted by Energy Dispersive X-Ray (EDX) test, static triaxial test, cyclic triaxial test, and measurement of pH value and heavy metal content, respectively. Content of BLAsh was evaluated in the constant total amount of cement and BLAsh content in the mixture. Based on the relationship among content of CaO, SiO_2, and the difference of maximum deviator stress (q_{max}) of mixture, it was concluded that BLAsh is able to replace cement totally. It was shown by same strength of totally cement replacement by BLAsh with the cemented bamboo chips-sandy soil mixture (without BLAsh). However, small amount of cement provided higher strength because CaO content in cement generates more $Ca(OH)_2$ as the result of cementation reaction and as the reactant in secondary pozzolanic reaction by BLAsh at once. Static and cylic triaxial test provide consistent result of the optimum amount of BLAsh. 75% of BLAsh content in replacing cement was the optimum mixture design in improving qmax and liquefaction resistance. In addition, positive effect of BLAsh addition to the environment was also presented by the decreasing pH value and heavy metal content.

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CHAPTER 5

ASSESSMENT OF LIQUEFACTION POTENTIAL ON LOOSE AND POORLY GRADED SANDY SOIL IMPROVED BY BAMBOO MATERIAL

5.1 Introduction

Based on the previous chapters, there were conclusions showed that bamboo chips and bamboo leaf ash (BLAsh) have abilities in improving loose and poorly graded sandy soil, especially in increasing the liquefaction resistance. Furthermore, this chapter focused on the assessment of liquefaction potential by proposed mixture design concluded by previous chapter following factual problem in field. Approach and adjustment were required and discussed in this chapter.

5.2 Literature review

5.2.1 Assessment of liquefaction potential

In Japan, the liquefaction index (P_L) is utilized in liquefaction potential assessment. This value is calculated based on the safety rate of liquefaction (F_L) for every depth. This procedure was proposed by Iwasaki et al. (1981). Furthermore, this method is utilized as specifications for highway bridges part V seismic in Japan Road Association. The value of F_L is defined by result of investigation in field, geological, and geomorphological conditions. Determination of liquefaction possibility and liquefaction potential by value of F_L and P_L, respectively, are shown in the Table 5.1. Iwasaki et al. (1981) explained the assessment of liquefaction potential by P_L. $P_L = 0$, it indicates that liquefaction potential is very low and detail investigation to the liquefaction is not required. $0 < P_L \leq 5$, it indicates that liquefaction potential is low, but detail investigation to the liquefaction is required on the important structure. $5 < P_L \leq 15$, it indicates high liquefaction potential and detail investigation to the liquefaction is required on the important structure. In addition, countermeasure of liquefaction is also required in general. $15 < P_L$, it indicates very high liquefaction potential. In this condition, detail investigation to the liquefaction and countermeasure of liquefaction are required. Hashizume et al. (2015) is one of the researchers that conducted the utilization and development of liquefaction potential assessment in Hachinohe area, Japan.

Table 5.1. Liquefaction Possibility and Liquefaction Potential (Iwasaki et al., 1981)

Liquefaction possibility		Liquefaction potential	
$F_L > 1.0$	Low	$P_L = 0$	Extremely low
$F_L \leq 1.0$	High	$0 < P_L \leq 5$	Low
		$5 < P_L \leq 15$	High
		$15 < P_L$	Extremely high

The rate of safety to liquefaction (F_L) (Equation 5.2) in every depth of the ground is defined by the dynamic shear strength ratio (R) and the seismic shear stress ratio (L) of the stratum. The required input data are peak ground acceleration (a), soil depth of the stratum, N-value, mean grain diameter (D_{50}), finer content (F_c), groundwater level, total stress (σ_v), and effective stress (σ'_v) of soil. In addition, type of earthquake is also considered in this calculation. The following are some requirement conditions to be satisfied in this method.

1. Alluvial sandy soil in principle
2. Saturated soil and groundwater level are shallower than 20 m and 10 m, respectively.
3. Soil with $F_c \leq 35\%$
4. Soil with $F_c > 35\%$ and $I_P \leq 15$
5. Soil with $D_{50} \leq 10$ mm and $D_{10} \leq 1$ mm

$$F_L = \frac{R}{L} \qquad [5.2]$$

The seismic shear stress ratio (L) is derived by the following equation.

$$L = \left(\frac{a}{g}\right) . \left(\frac{\sigma_v}{\sigma'_v}\right) . r_d \quad [5.3]$$

where, a : maximum acceleration at the ground surface or peak ground acceleration (gals)

g : acceleration of gravity (980 gals)

σ_v : total stress (kgf/cm^2)

σ'_v : effective stress (kgf/cm^2)

r_d : the reduction factor for dynamic shear stress (= 1.0 – 0.015z)

z : depth from the soil surface (m)

While, the dynamic shear strength ratio (R) is derived by equation below.

$$R = C_w . R_L \quad [5.4]$$

The following is the definition of modification coefficient reflecting characteristics of earthquake/seismic motion (C_w).

a. Type 1: seismic motion by great inter-plate earthquake with low occurrence frequency. Large amplitude acts for a long time repeatedly.

$$C_w = 1.0 \quad [5.5]$$

b. Type 2: seismic motion by large inland earthquake with very low occurrence frequency.

$$C_w = 1.0 \qquad (R_L \leq 0.1) \quad [5.6]$$

$$C_w = 3.3R_L + 0.67 \qquad (0.1 < R_L \leq 0.4) \quad [5.7]$$

$$C_w = 2.0 \qquad (0.4 < R_L) \quad [5.8]$$

Undrained cyclic shear resistance (R_L) is determined experimentally by N-value from geotechnical information database. The following are the equations to obtain R_L.

$$R_L = 0.0882\sqrt{N_a/1.7} \qquad (N_a < 14) \quad [5.9]$$

$$R_L = 0.0882\sqrt{N_a/1.7} + 1.6 \times 10^{-6}(N_a - 14)^{4.5} \quad (N_a \geq 14) \qquad [5.10]$$

where, N_a is amended N-value based on the grains size. For sandy soil, equations to obtain N_a are,

$$N_a = C_1 . N_1 + C_2 \qquad [5.11]$$

$$C_1 = 1.0 \qquad (0\% \leq F_c < 10\%) \qquad [5.12]$$

$$C_1 = (F_c + 40)/50 \qquad (10\% \leq F_c < 60\%) \qquad [5.13]$$

$$C_1 = F_c/20 - 1 \qquad (60\% \leq F_c) \qquad [5.14]$$

$$C_2 = 0 \qquad (0\% \leq F_c < 10\%) \qquad [5.15]$$

$$C_2 = (F_c - 10)/18 \qquad (10\% \leq F_c) \qquad [5.16]$$

while for gravelly soil, the equation as follows.

$$N_a = [1 - 0.36 . \log_{10}(D_{50}/2.0)] . N_1 \qquad [5.17]$$

where, D_{50} : mean grain diameter (mm)

N_1 : Normalized N-value for effective stress of 1 kgf/cm^2

$$N_1 = 1.7N / (\sigma'_v + 0.7) \qquad [5.18]$$

N : N-value acquired from Standard Penetration Test (SPT)

Hereinafter, liquefaction potential (P_L) is acquired by the weighted integration of F_L value for the depth. Input data is the distribution of F_L value to a depth of 20 m. The following is the equation to obtain P_L.

$$P_L = \int_0^{20} F . W(z)\, dz \qquad [5.19]$$

where, $F = 1 - F_L \qquad F_L < 1.0 \qquad [5.20]$

$F = 0 \qquad F_L \geq 1.0 \qquad [5.21]$

W(z) : weight function of the soil depth

$$W(z) = 10 - 0.5z \quad [5.22]$$

z : depth from the ground surface (m)

5.2.2 Parameter adjustment

In the assessment of liquefaction potential suggested by Iwasaki et al. (1981), as mentioned above, N_{SPT} value is the main input parameter besides characteristic of seismic motion, peak ground acceleration (a), soil depth of the stratum, N-value, mean grain diameter (D_{50}), finer content (F_c), groundwater level, total stress (σ_v), and effective stress (σ'_v) of soil. In order to obtain N_{SPT} value, in situ investigation by standard penetration test (SPT) is required. Some researchers conducted approach studies to obtain N_{SPT} value by other parameters. Hatanaka and Uchida (1996) summarized the empirical correlation between penetration resistance and internal friction angle of sandy soils in drained condition (Table 5.2). In addition, Sivrikaya and Togrol (2006) suggested the empirical equation to correlate between penetration resistance and undrained shear strength (S_u) on some soil types and some kinds of experimental tests such as Unconfined Compression, Unconsolidated Undrained Triaxial, and Field Vane tests. Focus on sandy soil application, especially fine-grained soil, they provided simple procedure as follows,

$$S_u = \alpha \cdot N \quad [5.23]$$

where, S_u : undrained shear strength (kPa)

α = 4.45 for N_{field}

= 6.35 for corrected N_{SPT}

Table 5. 2. Summary of Empirical Correlation between Penetration Resistance and Internal Friction Angle of Sandy Soils in Drained Condition (Hatanaka and Uchida, 1996)

Equation	Source
$\varphi_d = (20N)^{0.5} + 15$	Ohsaki et al. (1959)
$\varphi_d = (15N)^{0.5} + 15 \leq 45$ $(N > 5)$	Japan Road Association (1990)
$\varphi_d = (12N)^{0.5} + 25$ Angular and well-grained soil particles $\varphi_d = (12N)^{0.5} + 20$ Round and well-grained or angular and uniform-grained soil particles $\varphi_d = (12N)^{0.5} + 15$ Round and uniform-grained soil particles	Dunham (1954)
$\varphi_d = (0.3N)^{0.5} + 27$	Peck et al. (1953)

Notes:

φ_d : internal friction angle in drained condition (^{o})

N : N_{SPT} value

5.3 Research objectives

In order to contribute in solving factual problem, especially in Indonesia, this chapter was expected to perform the assessment of liquefaction potential using combination between the result of experimental study in this research and result of in situ investigation. Mixture applied in this assessment is optimum mixture concluded in the previous chapters to provide the effect to the field condition improvement.

5.4 Results and discussions

To present reducing liquefaction potential by utilization of bamboo material, factual problem was taken and simulated using the proposed mixture design concluded in previous chapter. Koseki et al. (2007) reported at 5:53 local time on Saturday, May 27, 2006, the Mid Java earthquake with moment magnitude (M_w) of 6.3 was measured. The epicentral depth of 10 km hit Yogyakarta City, Bantul, Sleman, Klaten, and Gunungkidul Districts in Java Island, Indonesia. The earthquake occurred at shallow depth in the overriding Sunda plate well above the dipping Australia plate. Reportedly, the extensive damage to houses due to this earthquake concentrated in lowland areas. It may be of fluvial process along existing or previous rivers by Quarternary young volcanic deposits of Merapi Volcano.

This study focused on the liquefaction occurrence in the public facility, i.e. Yogyakarta Airport sand boiling and cracking in the runway that can be seen in Fig. 5.1. There is information of soil data in the report by Koseki et al. (2007). Soil data used in this study was obtained in Kalitirto, Sleman District, nearby the location of occurred liquefaction. The data is summarized in Table 5.3. Dry unit weight (γ_d) and saturated unit weight (γ_{sat}) were calculated using assumption of natural moisture content in a saturated state (w_{sat} = 30%) for loose uniform sand soil suggested by Das (2006). Based on the physical properties of soil, all required conditions are satisfied to assess liquefaction possibility (F_L) by Japan Road Association method. In addition, N_{SPT} value as the result of in-situ investigation is also shown in Fig. 5.2. Based on the N_{SPT} value, the groundwater level (GWL) was about 2 m from ground surface. For a thickness of about 1 m, soft soil deposits with N_{SPT} values less than 10. This layer was ignored in the in-situ investigation, so it is not depicted in the profile of N_{SPT}.

Based on the data, liquefaction assessment was conducted to analyze the possibility and potential of liquefaction for each soil stratum. Furthermore, proposed improvement method using bamboo material was attempted to be applied in this case.

Figure 5.1. Sand boiling and cracking in the runway of Yogyakarta Airport and its vicinity. (Photos by Dr. Mardjono in Koseki et al., 2007)

Table 5.3. Data of Soil Physical Properties in Kalitirto, Sleman District (Modified after Koseki et al., 2007)

Parameter	Value
Coefficient of uniformity (U_c)	3.09
Finer content (F_c, %)	4.8
Maximum grain size (D_{max}, mm)	2.0
Mean grain diameter (D_{50}, mm)	0.28
Solid density (ρ_s, g/cm^3)	2.852
Dry unit weight (γ_d, kN/m^3)	15.06
Saturated unit weight (γ_{sat}, kN/m^3)	19.58
Plasticity index (I_p)	NP

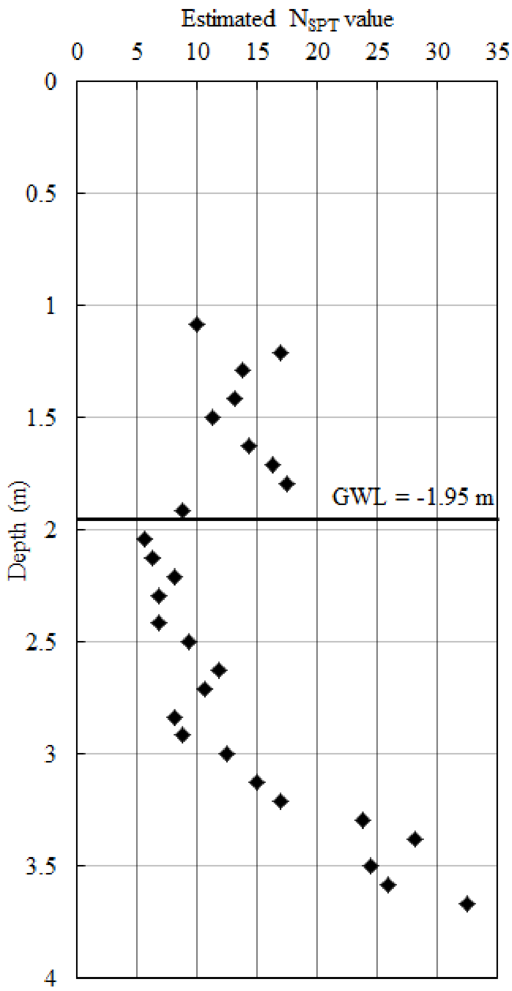
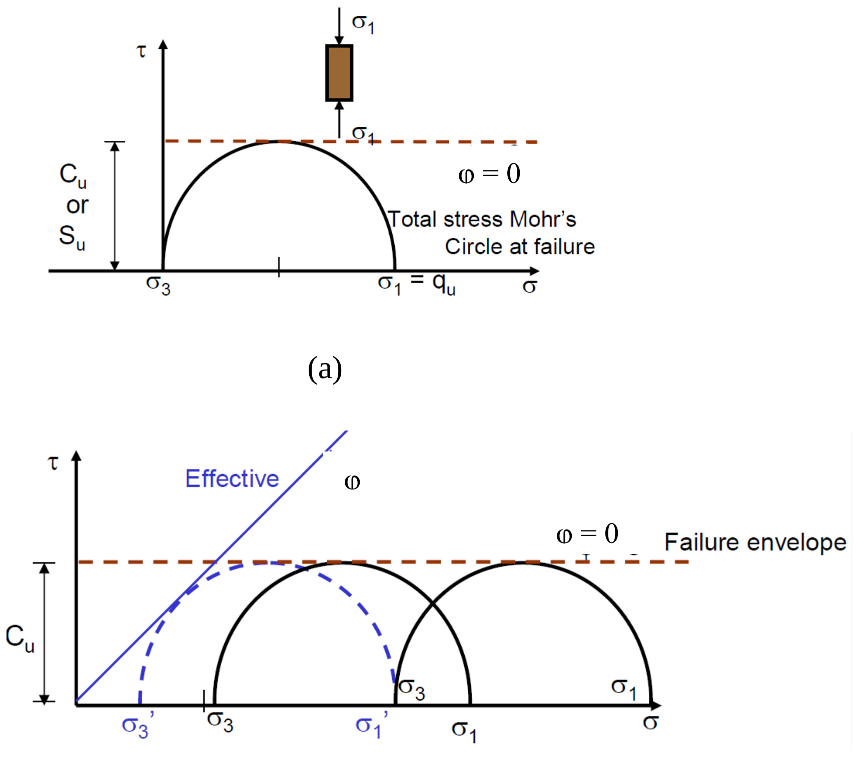


Figure 5.2. Profile of estimated N_{SPT} values at Kalitirto site, Sleman District, Yogyakarta, Indonesia. (Koseki et al., 2007)

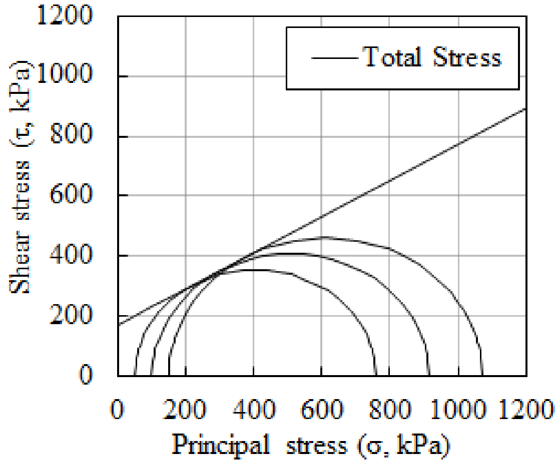
In this study, comparison between existing condition in field to the improved condition by proposed mixture using bamboo materials (bamboo chips and BLAsh) addition in the loose and poorly graded sandy soil was conducted. Proposed mixture used is the optimum mixture concluded in Chapter 4, i.e. 2% bamboo chips and 75% partially cement replacement by BLAsh in the 2% of total pozzolan content (total content of cement and BLAsh) mixed with sand soil (D_r = 35%). N_{SPT} value was obtained using empirical equation suggested by Sivrikaya and Togrol (2006) (Equation 5.23). As mentioned above, this equation was developed in undrained condition based on data obtained by Unconfined Compression, Unconsolidated Undrained Triaxial, and Field Vane tests. In this study, Consolidated Undrained Triaxial was conducted in determining the effect of bamboo chips and BLAsh in cemented poorly graded sandy soil. Compared to Unconfined Compression and Unconsolidated Undrained Triaxial, Consolidated Undrained Triaxial typically shows lower shear strength (Fig. 5.3). Thus, by this approach, data based on Consolidated Undrained Triaxial provides safer value of N_{SPT}. Regarding α coefficient, 6.35 of α was utilized in calculation to obtain corrected N_{SPT}, Figure 5.4 shows Mohr Circle of Consolidated Undrained Triaxial Test to the variation of BLAsh content in replacing cement conducted in Chapter 4. Total shear strength based on Consolidated Undrained Triaxial Test are summarized in Table 5.4.



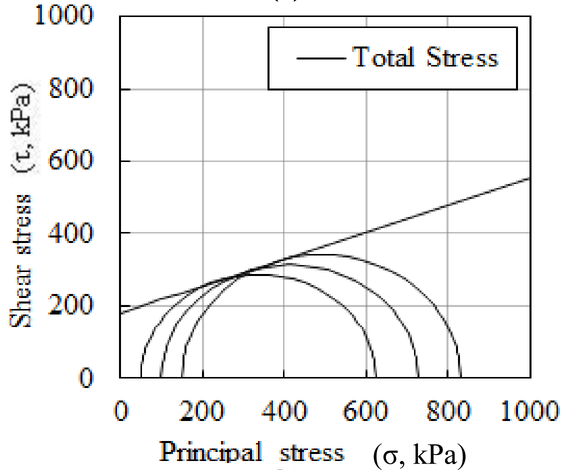
(a)

(b)

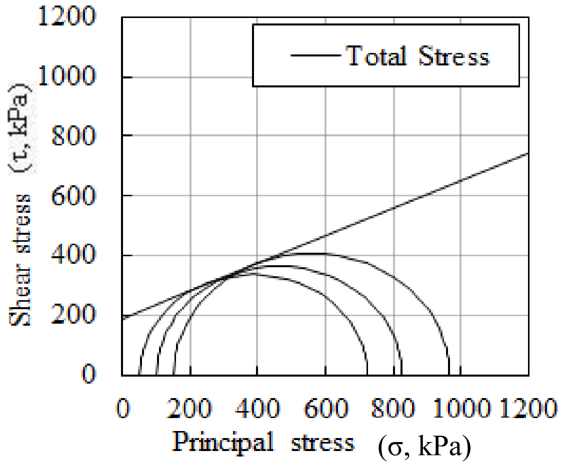
Figure 5.3. Typical result of (a) Unconfined Compression and (b) Unconsolidated Undrained Triaxial tests.


Total Stress
Shear stress (τ, kPa)
Principal stress (σ, kPa)
0
200
400
600
800
1000
1200

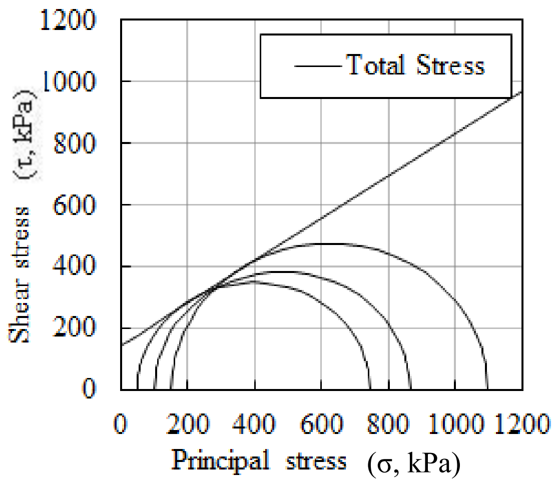
(a)


Total Stress
Shear stress (τ, kPa)
Principal stress (σ, kPa)
0
200
400
600
800
1000

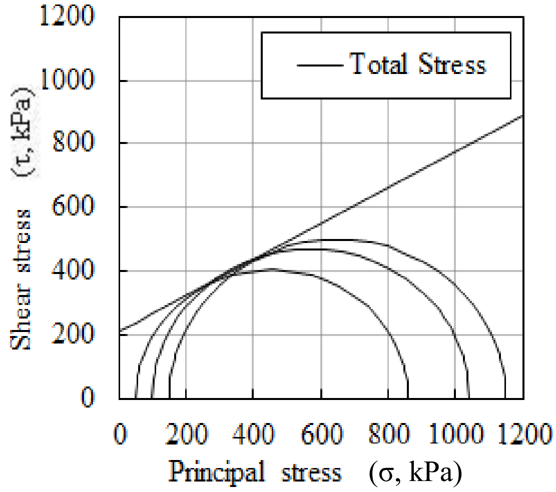
(b)


Total Stress
Shear stress (τ, kPa)
Principal stress (σ, kPa)
0
200
400
600
800
1000
1200

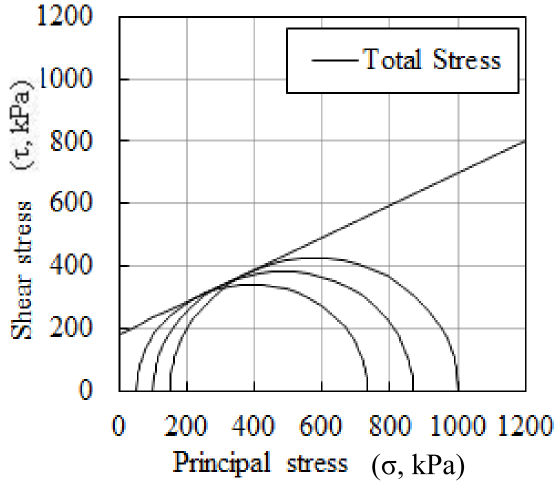
(c)



(d)



(e)



(f)

Figure 5.4. Mohr circle of the mixtures as the result of undrained triaxial test.

((a) TB_62, (b) $TC_{100}BL_0$, (c) $TC_{75}BL_{25}$, (d) $TC_{50}BL_{50}$, (e) $TC_{25}BL_{75}$, and (f) TC_0BL_{100})

Table 5.4. Summary of Mixture Properties

Mixture code	c_u (kPa)	$\varphi(^o)$	γ_b (kN/m^3)	γ_{sat}, (kN/m^3)	Corrected N_{SPT} value
$TB6_2$	170.02	31.11	20.54	17.36	26.77
$TC_{100}BL_0$	180.41	20.54	21.12	17.71	28.41
$TC_{75}BL_{25}$	190.56	24.76			30.01
$TC_{50}BL_{50}$	141.95	34.59			22.35
$TC_{25}BL_{75}$	210.41	29.56			33.14
TC_0BL_{100}	182.83	27.24			28.79

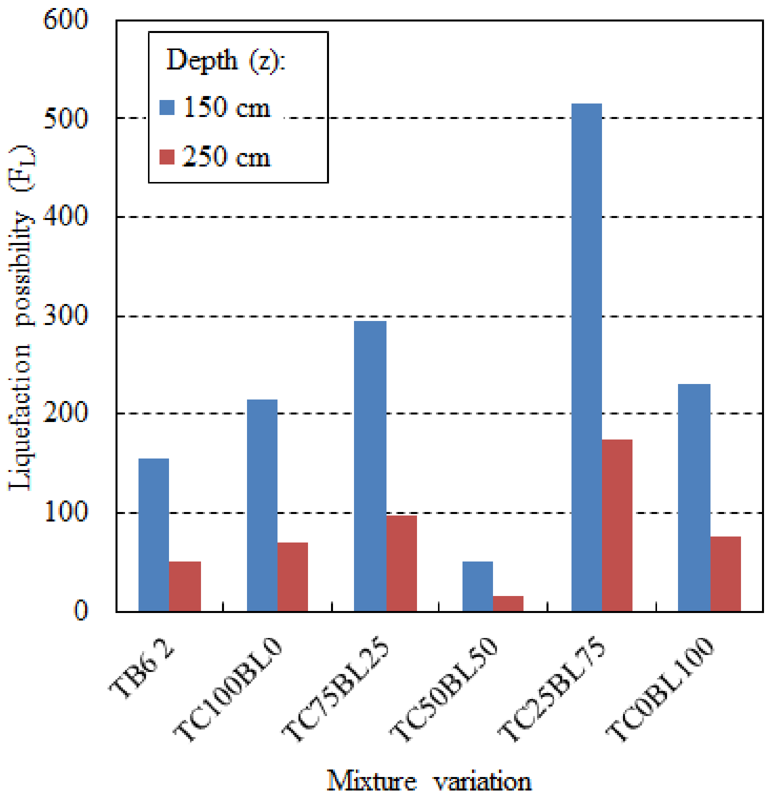


Figure 5.5. Comparison of F_L value based on mixture and depth variations.

Comparison results of liquefaction potential assessment are shown in Fig. 5.5. Code of each mixture variation follows explanations of specimen variation in the previous chapter (Table 3.1 and Table 4.2). Depth variation was conducted following the soil profile in Kalitirto site, Sleman District, Yogyakarta, Indonesia.

150 m depth shows the soil location above the GWL, whereas 250 m depth shows below the GWL. Based on this result, it depicts the increasing liquefaction resistance affected by increasing N_{SPT} value. Also, it was confirmed that liquefaction resistance decreases significantly under GWL. By its high strength, $TC_{25}BL_{75}$ provides highest improvement to the liquefaction potential. Thus, combination between 2% of 6 mm bamboo chips and 75% cement replacement by BLAsh provides significant improvement to the liquefaction potential.

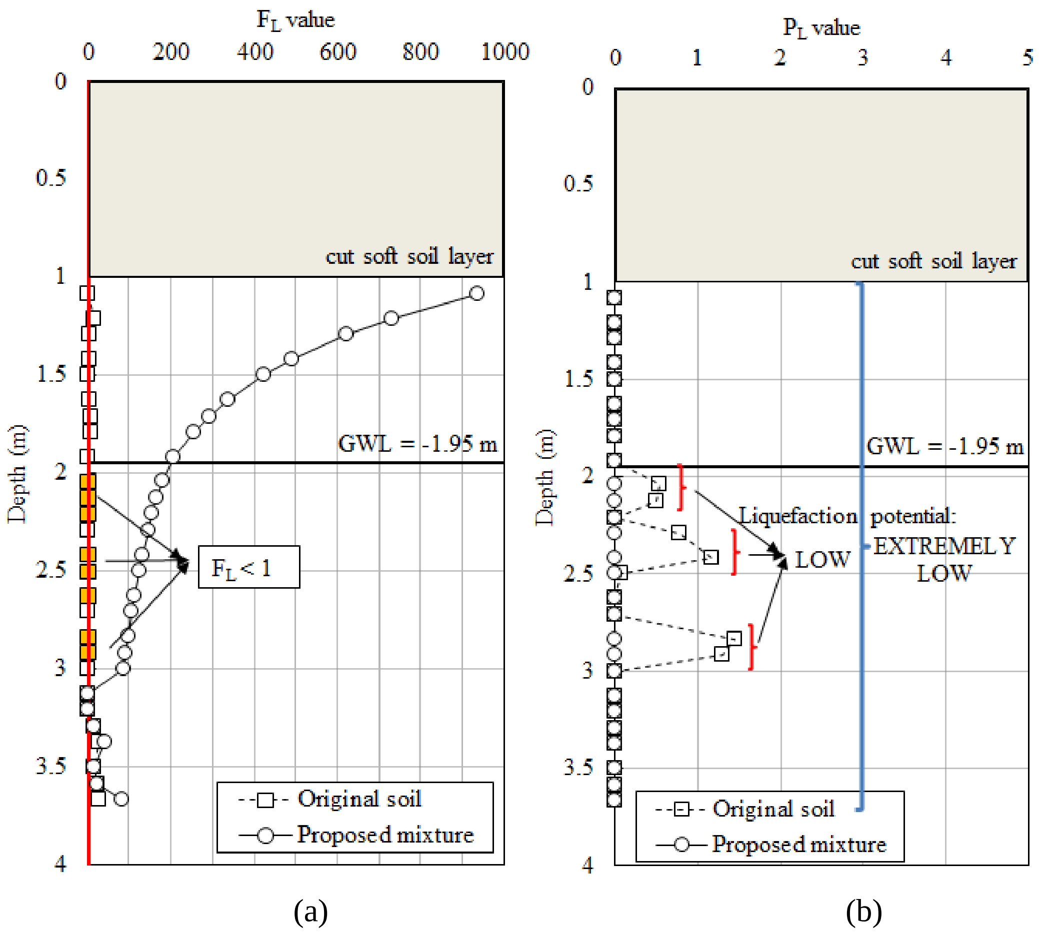


Figure 5.6. Comparison of (a) liquefaction possibility (F_L value) and (b) liquefaction potential (P_L value) between original soil and proposed mixture.

As the further investigation, F_L value comparison between original soil (soil in Kalitirto site, Sleman District, Yogyakarta, Indonesia) and $TC_{25}BL_{75}$ mixture (proposed mixture) was also presented in Fig. 5.6. This comparison provides information of F_L value for each depth. Original soil was drawn by dashed line, low values of F_L ($F_L \leq 1$) were obtained between soil depth of 2.04 m to 2.20 m, 2.42 m to 2.71 m, and 3.12 m to 3.29 m below ground surface. Based on Table 5.1, these values show that this soil stratum has high liquefaction possibility. According to the result of F_L analysis, P_L value was calculated and showed that this range of soil depth has low potential liquefaction ($0 < P_L \leq 5$). It can be confirmed that the reason is the low soil strength depicted by relatively low N-value. In addition, this range of soil depth is under GWL. As mentioned before, the trigger of liquefaction occurrence is poorly graded soil in the saturated condition. Also, based on Iwasaki et al. (1981), this condition required detail of investigation on the important structure. Following the result of analysis based on the site condition, the improvement using proposed mixture was applied to the depth of 3.20 m. In the Fig. 5.6, the improvement results were shown by continuous line. Based on the results, the increasing liquefaction resistance was confirmed by the increasing F_L value. Furthermore, P_L value also assured that the liquefaction potential is extremely low by the value equals 0.

5.3 Conclusions

Application of proposed mixture in factual problem in field, i.e. liquefaction occurrence after Yogyakarta Earthquake, Indonesia, on May 2006 was presented using Japan approach of liquefaction potential analysis. The assessment requires blow-count of Standard Penetration Test (N_{SPT}) value as the practical parameter in field. This chapter proposed the assessment by converting the result of undrained triaxial test as undrained shear strength (S_u) to N_{SPT} value following the empirical equation suggested by reference. The proposed mixture applied in this assessment is the optimum mixture concluded in the previous chapters, i.e. combination between 2% 6 mm bamboo chips and 75% cement replacement by BLAsh. Based on the result, decreasing liquefaction potential was shown significantly by the proposed mixture.

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CHAPTER 6

LIFE CYCLE ASSESSMENT OF BAMBOO LEAF ASH AS A PARTIALLY CEMENT REPLACEMENT IN BAMBOO CHIPS-SANDY SOIL IMPROVEMENT

6.1 Introduction

This chapter presents analysis related to the application in field. System is proposed to perform information about how to apply the bamboo material (bamboo chips and BLAsh) utilization in poorly graded sandy soil improvement. This system is expected to be utilized as a guidance to apply this proposed method in field. Furthermore, CO_2 emission as the result of the system, discussion about heavy metal content and pH, and also other aspects required to be considered are also shown in this chapter. This analysis is commonly referred as Life Cycle Assessment (LCA). Based on ISO 14040:2006, definition of LCA is compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Product has definition as material that leaves the unit process which in this study refers to BLAsh and cement. The followings are four phases in an LCA study:

1. goal and scope definition. It contains purpose, aim, and assumption used.
2. inventory analysis. It contains calculation of the environmental load.
3. impact assessment. It contains classification based on the result of inventory analysis to obtain information for each aspect.
4. interpretation, It contains review based on the results

6.2 Proposed system of bamboo material utilization

As mentioned above, this study proposes bamboo chips and BLAsh as the additional materials in cemented sand soil. For the application purpose, overview of this system is depicted in Fig. 6.1. This system contains collecting material, manufacturing process, storing product, distributing product, mixing, and spreading mixture in field.

Collecting bamboo materials as source is the main activity in this system. In tropical and subtropical countries, bamboo forest is very easy to be obtained due to its abundance. Bamboo trees consist of leaf, branch, culm, rhizome, and root. This study focuses on bamboo leaf producing BLAsh and bamboo culm producing bamboo chips. The harvesting system must be managed by selecting the mature bamboo at the proper season. Bamboo only requires 4-5 year in maturing process. Bamboo can be harvested annually continuously for about 30-40 years (Tariyal, 2016). Selecting bamboo trees by age is important to maintain the density and sustainability of bamboo forest. In addition, bamboo age also has relationship with both lignification and culm wall thickness (Lybeer, 2005). Agreed with Tariyal (2016), Lybeer (2005) mentioned that 44-months old bamboo (close to 4 years old) has mature cell wall. In natural or untreated condition without any process before cutting, bamboo was estimated to have the durability of 10-15 years in the appropriate technique and storage condition (Ghavami, 2008).

In manufacturing process, bamboo chips are produced by cutting bamboo culm using machine. The maximum length of bamboo chips can be set following the purpose of application. In this study, based on the conclusion in the previous chapters, the optimum maximum length of bamboo chips used is 6 mm. On the other hand, bamboo leaf is processed to be BLAsh by several steps. Dry bamboo leaf was burnt in an open air, stopped after it becomes black in color, and then heated in furnace at 600˚C for 2 hours to produce bamboo leaf in grey in color. Once heated, it was cooled and grinded using mortar and pestle, then sieved using 75 μm mesh wire. The BLAsh is made in the constant temperature (about 20ºC). One unit of dry mass of bamboo leaf is able to produce 10% BLAsh.

Regarding the requirement of storage, bamboo chips and BLAsh must be kept dry to prevent the growth of fungi and the agglomeration by air or water, respectively. Appropriate technique and storage of bamboo culm is also important to maintain the durability. For keeping the low water content, “air-dry” is more recommended because “oven-dry” system will decrease the strength of bamboo

(Jiang et al., 2012 and Li, 2009). In distributing process, bamboo chips and BLAsh are able to be provided through building materials store. Otherwise, these materials will be mixed directly with liquefiable soil, cement, and water by user following optimum mixture design. At the final stage, spreading the mixture as the improved subgrade soil is applied in road structure.

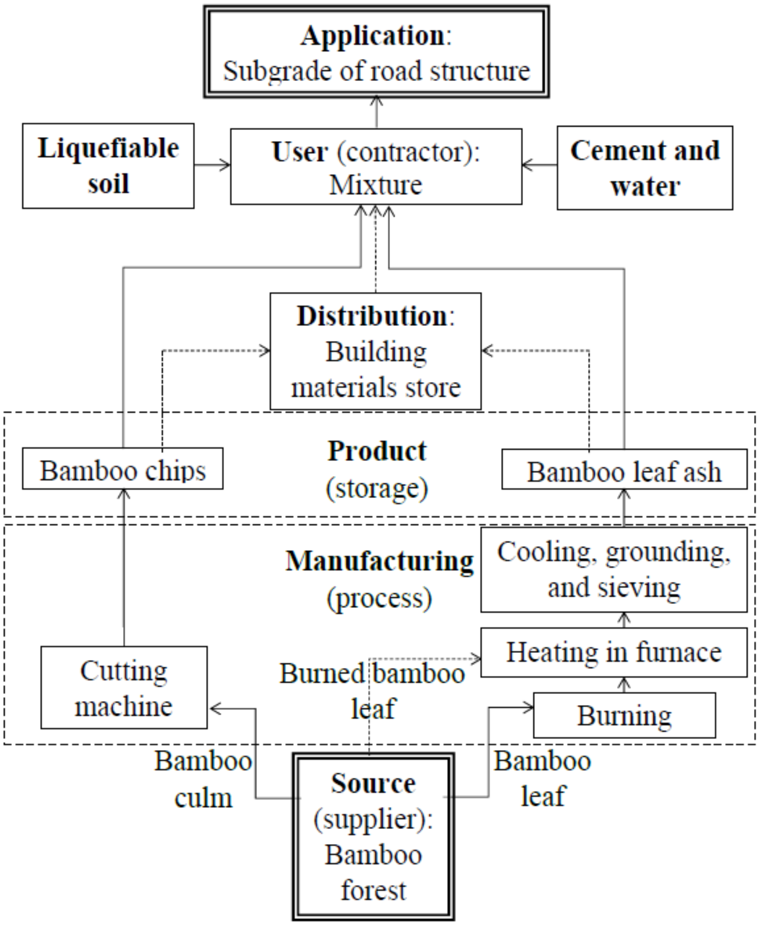

Figure 6.1. Overview of bamboo material utilization system in cemented sand soil.

Based on Shi et al. (2015), the bamboos of *Indocalamus sp.* have <50 leaves per plant. These plants in genus *Indocalamus* is native to China, Japan, Vietnam, and Sri Lanka. Shi et al. (2015) found the proportion of the total fresh leaf weight is more than 33% of fresh aboveground weight. Whereas, In Indonesia, especially in Sumatera Island, Malau et al. (2016) investigated the potential of bamboos of *Gigantochloa apus Kurz*. The percentages of dry weight of leaf and culm by total weight of biomass are 13.91% and 65.38%, respectively. These values are used to estimate potential amount of bamboo in poorly graded sandy soil improvement. In mass unit of improved sandy soil, it can be calculated the required mass of bamboo based on the optimum mixture design concluded in Chapter 4 (2% bamboo chips content and 75% cement replacement by BLAsh content of 2% total pozzolanic material). The calculation can be seen in Table 6.1. Based on this analysis, it can be approved that this method is able to reduce bamboo leaf waste of about 1.25 times of improved soil dry mass.

Table 6.1. Mass Potential of Bamboo Utilization

No.	Parameter	Value
1	Dry mass of improved sandy soil, M_1	1000 g
2	Mass of bamboo chips/bamboo culm, M_2 (2%)	175.87 g
3	Mass of bamboo leaf ash (BLAsh) , M_3 (75% of 2% total pozzolanic content)	131.90 g
4	Dry mass of bamboo leaf, M_4 (=10% x M_3)	1319.02 g
5	Average of ratio between bamboo leaf and bamboo culm, r (Malau et al., 2016)	37%
6	Mass of bamboo leaf by cultivated bamboo tree, M_5 (=M_2 x r)	65 g
7	Mass of bamboo leaf by collecting bamboo leaf waste (=M_4 – M_5)	1254.25 g

6.3 Evaluation of socio-environmental impact

Following the definition of LCA evaluation, this study investigates the socio-environmental impact of the BLAsh addition in cemented bamboo chips-sand soil in 4 stages below.

6.3.1 Goal and scope definitions

Goal of this study is to propose BLAsh to partially replace cement in soil improvement as applicable method in field. The intension of this study is to increase the value of bamboo leaf as environmental waste using simple manufacturing process. In this stage, investigation to the effect due to manufacturing process of BLAsh was performed. By this analysis, comparison between BLAsh and cement manufacturing process and impact to ecosystem were investigated to show the effectiveness of BLAsh in production process.

This analysis is limited to the manufacturing process of BLAsh and cement with the purpose of comparing two materials that have same function as pozzolanic materials. In addition, impact assessment focused on CO_2 emission as major direct greenhouse gas emission and heavy metal content in water flow through the mixture.

The following are assumptions used in this study:

1. Calculation of CO_2 emission was conducted to 1 kg mass product.
2. Information regarding calculation of CO_2 emission based on suggested method by Intergovernmental Panel on Climate Change (IPCC).
3. Comparison was conducted following the optimum mixture design concluded in Chapter 4 (75% cement replacement by BLAsh content of 2% total pozzolanic material). All activities other than manufacturing process of cement and BLAsh are same and constant among mixture variations. For obtaining investigation of cement replacement by BLAsh, discussion only focuses on comparison of manufacturing process of cement and BLAsh.

6.3.2 Life cycle inventory analysis

Combined with the proposed method by Inazumi et.al. (2015), this study considers the life cycle inventory based on the total cost to evaluate the life cycle cost comprehensively in social-ecological field. Total cost (T) contains direct cost (C), environmental cost (E), and project effect (B) (Equation 6.1). Each part follows the stages shown in Fig. 6.1.

Direct cost is considered as the mass-consumption society. In this study, by the process shown in Fig. 6.1, direct cost contains initial cost (C_I), processing cost (C_S), transportation cost (C_T), storing cost (C_K), and construction cost (C_C) (Equation 6.2). Initial cost is defined by cost consumed during the collecting process of bamboo as a source, such as harvesting activity. Processing cost is in the relationship with the cots consumed during manufacturing process, whereas transportation cost is fuel cost consumed per load and distance unit. Storing cost is defined by storage cost for each material per time unit. Construction cost is consumed during the process of mixing and spreading the mixture as the improved subgrade in road structure construction.

Environmental cost (E) is required as the quantification of the impact to the environment due to the system. This value is utilized as the consideration in applying the system in field and determining the feasibility of the system. Following condition of the system, this study utilizes 3 types of environmental cost, i.e. environmental cost during the manufacturing process (E_0), environmental cost consumed by transportation (E_T), and environmental cost by impact to ecosystem (E_C) (Equation 6.3). Environmental cost during manufacturing process is defined by the conversion from quantity of CO_2 emitted by each process in manufacturing stage to the monetary unit. This value is very important to provide information regarding the impact of the process to the climate change issue. Environmental cost by transportation also discuss about CO_2 emitted by transport activity during system operation. This value depends on distance, type of transportation and fuel type used. Price of CO_2 is about 25\$/kg-CO_2 following the recommendation of International Monetary Fund by Litterman (2013). Environmental cost by impact to ecosystem is defined by conversion from heavy metal content carried by water flowing through the system to the monetary unit. Chemical component in cement and BLAsh material is the main concern in this consideration. Limitation of heavy metal content is in relationship with the healthy concern. Generally, this requirement is provided by each country in drink water guidelines.

Project effect (B) is in relationship with the disposal cost. In this study, residual material is resulted by manufacturing process. Generally, this value is obtained by multiply the volume of residual waste (W) with the unit price of disposal activity (S).

$$T = C + E + B \qquad [6.1]$$

$$C = C_I + C_S + C_T + C_K + C_C \qquad [6.2]$$

$$E = E_0 + E_T + E_C \qquad [6.3]$$

$$B = W \times S \qquad [6.4]$$

To determine the environmental CO_2 emission, flow chart of manufacturing process of bamboo leaf ash is performed in Fig. 6.1, whereas CO_2 emission calculation of manufacturing process of cement followed standard process commonly applied in cement companies. So, the cement manufacturing process is not performed in detail here. However, calculation of CO_2 emission is based on the standard in IPCC (2006a). Production process of clinker, as intermediate product in cement manufacture, is the most part that emits CO_2. In addition, CO_2 is also emitted during the calcination of cement kiln dust (CKD). These factors are considered in the calculation of total CO_2 emission of Portland cement production.

In this study, evaluation of impact to environment by CO_2 emission is calculated for the manufacturing of 1 kg for each BLAsh and cement due to the comparability concept. The CO_2 emission by transportation during process is not included. However, the calculation of each process that emits most CO_2 during process is considered in detail. The result of CO_2 emission calculation is performed in Table 6.2.

In the production of BLAsh, electrical power was used for heating the burned bamboo leaf. The power of muffle furnace is 1.5 kW at 1100 ℃. It is assumed that the power consumption is proportional to the temperature. In this purpose, temperature of furnace was set to 600 ℃. Other parameters and correction factors considered in process of clinker production, cement kiln dust, and burning in open air were referred to guidance suggested by IPCC.

Regarding the comparison of impact to environment between cement and BLAsh in the mixture, heavy metal content and pH measurement were discussed in Chapter 4.

6.3.3 Assessment of environmental impact

In the manufacturing process of BLAsh, bamboo leaf as raw material is waste. So, energy released is at the stage in an open air burning and heating in furnace. In the burning in an open air, fuel is not required. Fire is generated by dried bamboo leaf burning. Complete combustion was conducted until dried bamboo leaf becomes black. The, the burning result was calcined in electrical furnace at 600 ℃ for 2 hours. This process produces bamboo leaf in grey color. In this process, potential negative environmental impacts may be associated by the calcination process of electrical fuel. The next stages are focused on the changes of physical performance of calcined bamboo leaf, i.e. grinding and sieving. Fuel energy is not required in these both processes, so CO_2 is not emitted. BLAsh is the product passes the 75 μm sieve mesh. The waste byproducts obtained is at a rate about 2% to dry mass of dried bamboo leaf. Mass reduction of bamboo leaf as environmental waste is a good achievement.

The total emission of CO_2 by BLAsh production is about 10 times more than Portland cement production that can be seen in Table 6.2. This result is very high value in total. The high CO_2 emission is produced by burning process in open air. It is the reason of the strictly regulation of waste open burning, especially in developed countries. However, developing countries still utilize this method to reduce the volume of bamboo leaf as an agriculture waste directly in the bamboo forest. This activity is able to cut off the manufacturing process of BLAsh by only heating the burned bamboo leaf produced by local bamboo farmer. Regarding the CO_2 emission by heating furnace using electrical power, the value is estimated by the world average data in Assessment Report of IPCC written by Sims et.al. (2007). It will vary depending on country by the source or power plant used. However, the high CO_2 emission by open burning process becomes another problem to environment.

Table 6.2 Calculation of CO_2 Emission (/1 kg product)

Product	Process	kg-CO_2	Parameters	CO_2 emission (kg-CO_2)
PC	Clinker production	0.507/kg clinker*	96% clinker in 1 kg cement	0.487
	CKD	6% of CO_2 emission by clinker*	-	0.029
Total CO_2 emission of PC				0.516
BLAsh	Burning in open air	(SW x dm x CF_i x $FCFi$ x OF_i) x 44/12** where, SW x dm = total dry weight of waste CF_i = total carbon content $FCFi$ = fraction of fossil carbon in total carbon OF_i = oxidation factor 44/12 = conversion factor from C to CO_2	- 10% BLAsh/kg dry weight of bamboo leaf SW x dm = 10 kg - CF_i = 49% for garden and park waste - FCFi = - for garden and park waste - OF_i = 58% for open burning practice	4.226
	Heating furnace	0.540/kWh***	Capacity = 1.5 kW/1100 ^oC 600^oC for 2 hours	0.886
Total CO_2 emission of BLAsh				5.112

Notes: PC=Portland Cement, CKD=Cement Kiln Dust, BLAsh=Bamboo Leaf Ash.

References: *IPCC Guidelines, 2006a; **IPCC Guidelines, 2006b; and ***Assessment report of IPCC by Sims, 2007.

Regarding the heavy metal content and pH value measurement. As discussed in Chapter 4, only Cadmium (Cd) content that showed high concentration above the allowance limit following guideline of drinking-water quality. However, BLAsh utilization showed high advantages in reducing heavy metal content and better alkalinity in the effluent water.

6.3.4 Interpretation of life cycle assessment

Carbon sequestration is one of the solutions of high CO_2 emitted by BLAsh production. This topic is developed in many researches which covers the strategy of carbon management to mitigate the increasing CO_2 emission (Song et al., 2011; Bahtiar et al., 2012; Thokchom and Yadava, 2015). The ability of bamboo trees itself to decrease atmospheric carbon by photosynthesis activity was widely investigated in this topic. By its world record as the fastest growing plant, bamboo is not only able to grow 91cm/day, but also has high potential of carbon sequestration about 275,190-302,711 kg-CO_2/ha (Nadapdap and Purwanto, 2013). It becomes high potential of naturally cycle of CO_2 emission by bamboo itself. As mentioned before, in the developing country, open burning system is conducted in the bamboo forest directly. By this condition, the passive effort of CO_2 reduction by bamboo tress itself through photosynthesis process is reliable.

Information about density of bamboo trees in culms/ha unit, bamboo as biomass in kg/ha, and ratio between bamboo leaf and bamboo culm per plant are important in determining the carbon cycle of BLAsh production and photosynthesis performance. Biomass is defined by total dry weight of organic matter per unit area (Brown, 1997). However, besides the variation of genera and species of bamboo itself, environmental factors are very sensitive to affect the growth parameters of bamboo trees, such as altitude, temperature, and rainfall (Tariyal, 2016). Shi et.al. (2015) confirmed that the bamboo of *Indocalamus sp*. has density about 76 ± 19 to 291 ± 22 plants per m^2. In Indonesia, Malau et.al. (2016) and Sujarwo (2016) mentioned biomass of *Gigantochloa apus Kurz*. is about 10,900-11,270 kg/ha. However, as mentioned above, genera and species affect the special density (plants per unit area) (Fig. 6.2). This study focuses on the bamboo widely spread in Indonesia, i.e. *Gigantochloa apus Kurz*. Refered to the information of carbon sequestration by Nadapdap and Purwanto (2013) carbon sequestration of 1 kg bamboo tree can be calculated, i.e. 26 kg-CO_2. Therefore, at the same mass unit, 1 kg bamboo tree is able to absorb about 5 times CO_2 emitted by 1 kg BLAsh production (Fig. 6.3). This value is high and potential to be the solution. However, harvesting management by selecting proper age of bamboo trees is the major concern to provide sustainability of bamboo forest and cycle of carbon. 4-5 years was suggested as the optimum age of bamboo trees to be harvested. Utilization of fallen bamboo leaf rather than the fresh one is highly recommended in order to reduce the environmental waste. In addition, due to the ability of carbon absorption by bamboo trees itself, manufacturing process is also recommended to be developed or established near the bamboo forest. It is also to achieve effectiveness of production. By this analysis, CO_2 emission by BLAsh can be neglected as long as the recommendations regarding manufacturing process are applied. Thus, environmental cost by CO_2 emission is calculated by cement production only. Following the price of CO_2 equals 25$/kg-$CO_2$ (Litterman, 2013), utilization of BLAsh in replacing 75% of cement addition in mixture is able to reduce 1.935$ in 1 kg of improved sandy soil.

(a) (b)

Figure 6.2.Bamboo species of (a) *Indocalamus sp*. and (b) *Gigantochloa apus Kurz*. (Source: http://bamboosourcery.com and https://id.wikipedia.org/wiki/Bambu_tali)

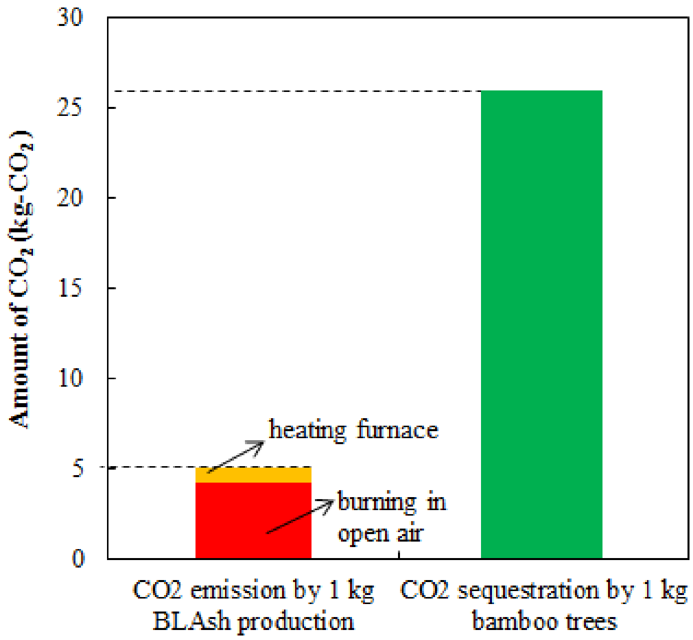

Figure 6.3. Comparison between CO_2 emission by BLAsh production and CO_2 sequestration by bamboo trees.

Regarding the cost of project effect by disposing activity in BLAsh production, 2% of residual material is relatively small compared to unmaintained volume of fallen bamboo leaf as environmental waste and/or volume of burned bamboo leaf produced by local bamboo farmer without any further process. This reduction is able to prove that cost of the disposing activity by BLAsh production is less than the disposal cost of unused bamboo leaf naturally. In addition, this amount of residual material is obtained by grounded ash that does not pass the 75 μm mesh wire. In other fields, this material that does not satisfy the size requirement of ash still can be used chemically as purifier (Mulyono et.al., 2012 and Muangthai et.al., 2016). Thus, integrated system with other fields for using residual material of BLAsh production is highly recommended to provide environmentally friendly method without disposed residual material.

6.4 Conclusions

Partially replacing cement by BLAsh is one of the methods to reduce environmental problem in geotechnical field. The following are the conclusions of this study:

1. By analysis result of bamboo trees potential, this method is able to reduce bamboo leaf waste of 1.25 times of improved soil dry mass.
2. In the life cycle inventory analysis, equation of total cost of this method was proposed.
3. By $LCCO_2$ evaluation, comprehensive analysis was discussed to prove that environmental problem by BLAsh production is able to be solved by the high ability of bamboo trees itself to absorb CO_2 emission (carbon sequestration). Thus, CO_2 emission by cement production is reduced by decreasing cement content in mixture.
4. Regarding the concern to maintain the sustainability of bamboo forest itself, bamboo selection and harvesting time management were recommended in applying this method in field.

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CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH WORK

7.1 Conclusions

Goal of this research is provide comprehensive study on utilization of natural material in geotechnical field. By this research, higher sense of tolerance to the environmental aspect in finding technical solution is expected. Based on this study, bamboo as an abundant natural resource was proposed to solve the problem of loose and poorly graded sandy soil. The following are the conclusions summarized for each chapter.

Chapter 2 concluded that addition of bamboo flakes and bamboo chips improves loose and poorly graded sand strength in undrained and saturated condition. In order to determine the optimum type between bamboo flakes and bamboo chips, water absorbability test apparatus was developed. In the constant volume of bamboo flakes and bamboo chips, relationship between water absorbability and elapsed time was determined using this simple test apparatus. In addition, physical characteristic, mechanical properties, and microscopic analysis of bamboo material addition in cemented sandy soil improvement were examined by elongation-flatness ratio, static triaxial test, and Scanning Electron Microscopic (SEM) test, respectively. It was found that cutting machine produces intact structure of bamboo chips, whereas rubbing machine produces fiber structure of bamboo flakes. The form of structure affects the water absorbability and mechanical properties of bamboo material in cemented sandy soil. Based on the comparison, intact form of bamboo chips provides higher performance compared to bamboo flakes by the consistent water absorbability and the higher shear strength in cemented sandy soil mixture.

Chapter 3 concluded that bamboo chips are reliable as the reinforcement material in cemented sandy soil instead of cement replacement. It was shown by negative tendency of bamboo chips-sandy soil mixture to the permeability and dilative behavior compared to cemented sandy soil. Conversely, the addition of bamboo chips in cemented sandy soil provides positive tendency. Furthermore, 6 mm bamboo chips provided optimum result on the improvement of permeability and dilative behavior compared to 10 mm bamboo chips.

Chapter 4 concluded the effect of BLAsh in cemented bamboo chips-sandy soil mixture based on chemical properties by EDX test, mechanical properties by static triaxial test, liquefaction resistance by cyclic triaxial test, and impact to the environment by measurement of pH value and heavy metal content. Content of BLAsh was evaluated in the constant total amount of cement and BLAsh content in the mixture. Based on the relationship among content of CaO, SiO_2, and the difference of maximum deviator stress (q_{max}) of mixture, it was concluded that BLAsh is able to replace cement totally. It was shown by same strength of totally cement replacement by BLAsh with the cemented bamboo chips-sandy soil mixture (without BLAsh). However, small amount of cement provided higher strength because CaO content in cement generates more $Ca(OH)_2$ as the result of cementation reaction and as the reactant in secondary pozzolanic reaction by BLAsh at once. Static and cylic triaxial test provide consistent result of the optimum amount of BLAsh. 75% of BLAsh content in replacing cement was the optimum mixture design in improving qmax and liquefaction resistance. In addition, positive effect of BLAsh addition to the environment was also presented by the decreasing pH value and heavy metal content.

Chapter 5 contributed to the application of proposed mixture design utilization to the factual problem in field. Assessment of liquefaction potential was performed by using data of liquefaction occurrence after Yogyakarta Earthquake, Indonesia, on May 2006. It was conducted using Japan approach of liquefaction potential analysis. The assessment requires blow-count of Standard Penetration Test (N_{SPT}) value as the practical parameter in field. This chapter proposed the assessment by converting the result of undrained triaxial test as undrained shear strength (S_u) to N_{SPT} value following the empirical equation suggested by reference. The proposed mixture applied in this assessment is the optimum mixture found in the previous chapter, i.e. 75% cement replacement by BLAsh. Based on the result, decreasing liquefaction potential was shown significantly by the proposed mixture.

Chapter 6 concluded that partially replacing cement by BLAsh is one of the methods to reduce environmental problem in geotechnical field. Life cycle assessment (LCA) of BLAsh utilization in liquefiable soil improvement was conducted. In addition, application system of bamboo material utilization was generated. Based on the system, reducing bamboo leaf waste was calculated, equation to calculate total cost of system was proposed, and life cycle CO_2 ($LCCO_2$) of BLAsh production was presented. By $LCCO_2$, high CO_2 emission was shown in BLAsh production. However, the high carbon sequestration of bamboo trees was proposed to solve this problem. Regarding the concern to maintain the sustainability of bamboo forest itself, bamboo selection and harvesting time management were recommended in applying this method in field.

7.2 Future research works

Based on the conclusions above, bamboo material shows positive tendency in improvement of poorly graded sandy soil in various points of view. However, there are some recommendations and suggestions in utilization of bamboo material as a new material in geotechnical application. These recommendations listed below are used as the foundations to deepen the investigation and analysis in future research work.

1. As the requirement of subgrade material in road structure construction, California Bearing Ratio (CBR) test is recommended to be conducted to complete the information of bamboo material utilization in poorly graded sandy soil.
2. Comparison among variation of bamboo species or variation of bamboo obtained from several different places is recommended to generalize the effectiveness of bamboo material in poorly graded sandy soil.

3. Longer curing time during preparation of specimen is recommended to perform the durability of bamboo material, especially bamboo chips, in the mixture after long term period.