Mechanical and leaching characterization of inert waste landfills for safe and sustainable management

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Abstract

Inert wastes such as construction and demolition waste, rock, glass, metals, plastics, woods etc. are disposed at the inert waste landfills in Japan. Presently, the inert waste landfills follow the design instructions of the municipal solid waste (MSW) landfills because of the unavailability of design instructions for inert waste landfills. The MSW design instructions are considered as too conservative for the inert waste landfills because the composition of the inert waste is different than the MSW. A better understanding of composition, physical characteristics, mechanical characteristics, leaching characteristics of inert wastes is needed to check the waste fill stability, embankment stability and leachate chemistry. In this thesis, the test and design methods for safe and sustainable inert waste landfills are discussed. This entire research is broadly divided into three parts namely- (a) In-situ and laboratory mechanical tests for mechanical characterization of inert waste, (b) Lysimeter, laboratory column, and laboratory batch leaching test to understand the leaching behavior inert waste, and (c) Slope stability analysis with centrifuge model test and FEM dynamic analysis.

(a) In-situ and laboratory mechanical tests for mechanical characterization

The composition of an inert waste landfill is important from the geotechnical point of view because the concrete and rock wastes help in increasing the bearing capacity of the landfill and the fibrous fractions can act as reinforcement by providing tensile resistance to increase the volume of the inert waste landfill. The physical and mechanical characteristics were examined at inert waste landfills in Japan, aiming at establishing a safe and cost-effective design method specific to inert waste landfills. Composition analysis, basic physical properties, angle of repose, CASPOL impact value test, and in-situ direct shear test were conducted. Wide variety in composition was found for three main components which were: fibrous content with a range of 3.6 to 54%, granular content from 13 to 45%, and soil-like content from 43 to 74%. Water content increased and percentage air voids decreased with an increase in fibrous content and age after reclamation. Impact value, an indicator of bearing capacity, increased with the increase in dry density. For the direct shear test, cohesion (c) and internal angle of friction (φ) were found within the range of 2–21 kN/m^2 and 22–59^o respectively. The shear stresses obtained from these c and φ values were higher than the municipal solid wastes, particularly for landfills having fibrous fractions ranging from 14 to 30% and under the normal stress of 25.55 kN/m^2. 'c' increased and 'φ' decreased with increase in dry density, age

after reclamation, and impact value. The correlation calculated for c and φ with impact value for inert waste landfill were $c = 4.10\ I_a - 21.32$ and $\varphi = -4.61\ I_a + 82.37$. Laboratory direct shear test and laboratory triaxial tests were also conducted with inert waste collected from the landfill sites to check the effect of fibrous fractions on shear strength characteristics and to compare the results with the in-situ shear strength tests. In laboratory direct shear tests, four samples of inert waste with 3, 6, 11 and 16% fibrous content were tested. The internal friction angle first increased, then decreased with an increase in the proportion of fibrous fractions to a certain extent and the cohesion first decreased and then increased. In laboratory triaxial test conducted with inert waste having 0, 0.5 and 1% fibrous contents, deviatoric stresses increased with increase in confining pressure and fibrous content. With an increase in axial strain under confining pressures of 60 and 90 kPa, the volumetric change of 0% fibrous content showed similar behavior as dense sand and that of 1% fibrous content was similar to loose sand. For 0.5% and 1% fibrous content under high confining pressure, deviatoric stress increased after a certain axial strain, indicating inert waste with fibrous content may show higher shear resistance under high axial strain condition.

(b) Lysimeter, column and batch leaching tests on inert waste materials

The presence of fibrous fractions in inert waste may cause storage of water inside the inert waste landfill and there are also some possibilities of the presence of toxic and degradable matters in the inert waste materials. In this research, lysimeter tests were carried out with various configurations to check the leaching of contaminants and to determine a better reclamation method. Lysimeter drainage results showed that the retention property of leachate was dependent on the reclamation method. Sorption of dissolved toxic materials present in the leachate by the soil was confirmed. Although an increase in the concentration of chemical parameters or metals in the leachate was observed from highly compacted reclamation, the concentrations were found within the standard limits. In the laboratory column leaching test, the change in the leachate behavior was observed due to variation in fibrous contents of 2% and 10% in the inert waste. The water storage and dissolved parameters were found lower for the column with 10% fibrous content than that of 2% fibrous content. TOC was found higher for 2% fibrous content, but the values were found to be within the standard limit. With high fibrous content, the density became lower, thus increasing the drainage and decreasing the water-waste contact time. Soil layer installation seemed to be an effective solution for sorption of heavy metals etc. and buffering capacity. From the column leaching test, it was confirmed that the higher fibrous content in the waste materials does not store leachate if they are smaller in size. Batch leaching test was also conducted before the column leaching test. The batch leaching test was conducted to have a quick estimation of the amount of heavy materials present in the leachate. The results of the batch leaching test can also be used as an alternative for lysimeter and laboratory column test, but the results obtained may not be very precise as it is a quick leaching test.

(c) Slope stability analysis with centrifuge model test and dynamic analysis

The strength parameters obtained from the in-situ test were used in slope stability analysis. Centrifuge model test and dynamic analysis on landfill models under small and large earthquake conditions were carried out. In the centrifuge model test, models of landfills with 1:1 gradient slope were made of silica sand mixed with and without fibrous content and input acceleration were applied within the range of 100-400 gal. For lower values of acceleration (100-200 gal), landfills and embankments were stable, but for higher values (300-400 gal), remarkable damages of slopes were observed. In case of rigid embankments (made of cement improved soils), slope failure occurred with a slide of embankment due to change in earth pressure from passive to active condition (passive failure mode). Without fibers, a complete slide of upper and lower embankment occurred. In case with landfill model with fiber, overburden pressure in the lower layer was larger than the upper layer and fibers contributed to tensile resistance; thus, little damage was observed. Significant slide was observed in the upper embankment for landfill models with fiber for higher values of acceleration (300-400 gal) because of heavy transmission of shaking force from lower (fiber reinforced) rigid landfills. One case of centrifuge model was also made by compacting the top layer from 60% relative density to 90% relative density, but complete resistance to sliding of embankment could not be achieved. In-situ density, water content, and shear wave velocity were used as input parameters for dynamic analysis. In dynamic analysis, models of landfills with embankments of cement improved soil or cohesive soil were tested with and without fiber. Three models were selected with slope gradients of 1:1, 1:1.5, and 1:2. For cement improved (rigid) condition, small earthquake (L1) showed smaller non-linearity of the embankment and waste layer, and integral behavior of the slope; however, for larger earthquake (L2), non-linearity predominated to non-integral behavior and embankments acted against the earth pressure. Damage of upper embankment can be repaired easily but this phenomenon should be considered in the design of

landfill slopes. From static and dynamic slope stability analysis, the possibility of making a steeper slope than the existing inert waste landfill was confirmed. The dynamic analysis demonstrated the failure condition of slopes during a heavy earthquake.

In conclusion, within a specific limit, the fibrous fractions present in the inert waste improved the shear strength of the waste and showed improvement in the slope stability during earthquake condition. The leaching test confirmed the safety of the quality of the leachate generated in the inert waste landfills. Possible storage of leachate in large fibrous fractions inside the inert waste landfill can be reduced by using fibrous fractions of 10-15 cm size. Therefore, in place of the existing slope, a steeper slope can be recommended to increase the storage capacity of the inert waste landfills. Steeper slopes can reduce the burden of finding more land areas for the construction of new inert waste landfills. Moreover, if mechanical tests confirm the high bearing capacity and slope stability of the inert waste landfill, then after closure of the landfill, the area can be reused to construct some new facilities. Appropriate land use and reuse of inert waste landfills can reduce the negative impacts on the environment and encourage sustainability.

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List of notations

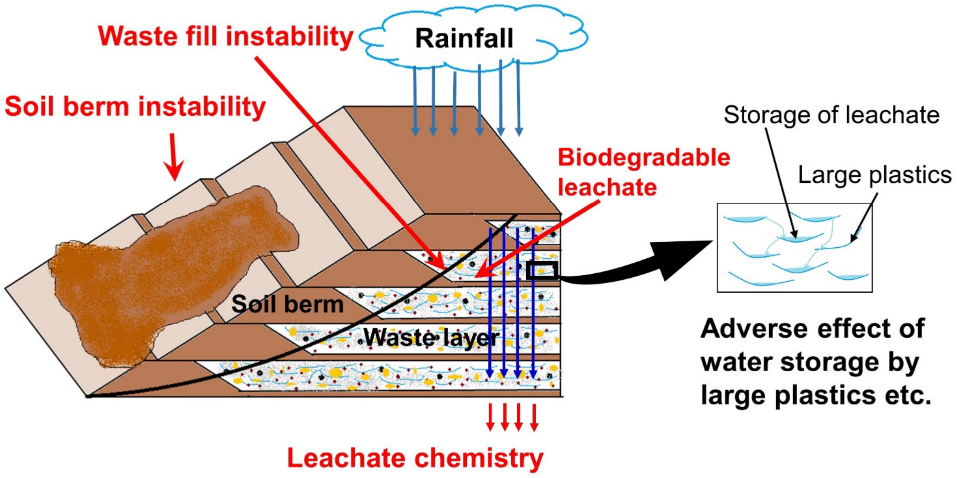
As	Arsenic
B	Boron
c	Cohesion
c'	Effective cohesion
CH_4	Methane
D_r	Relative density
E	Young's modulus
EC	Electrical Conductivity
Eh	Oxidation-reduction potential
G_f	Specific gravity of fibrous fractions
G_g	Specific gravity of granular materials
G_s	Specific gravity of soil fractions
G_c	Calculated specific gravity
G_F	Field specific gravity
G_o	Initial shear modulus
G_{max}	Shear modulus at very low strain
h	Hysteresis damping ratio
H_2S	Hydrogen sulfide
I_a	CASPOL impact value
K_o	Coefficient of earth pressure at rest
K_{30}	Ground reaction co-efficient
L_1	Small scale earthquake
L_2	Large scale earthquake
L_s	Volume of the wet sample
L/S	Liquid to solid ratio
n	Coefficient of confining pressure
n_a	Percentage air voids
Pb	Lead
P_f	Percentage of fibrous fractions
P_g	Percentage of granular fractions
P_s	Percentage of soil fractions
q_u	Unconfined compressive strength
SO_4^{2-}	Sulfate ion
SPT	Standard penetration test
SS	Suspended solid
TOC	Total Organic Carbon
T-N	Total Nitrogen
V_s	Shear velocity
w	Water content
W_o	Weight of dry sample
W_w	Weight of wet sample
α_a	Repose angle after avalanche
α_c	Critical repose angle

φ	Internal angle of friction
φ'	Effective internal angle of friction
θ	Volumetric water content
σ	Normal stress
τ	Shear stress
γ	Shear strain
γ_{d}	Dry unit weight
γ_{w}	Unit weight of water
γ_{y}	Reference shear strain

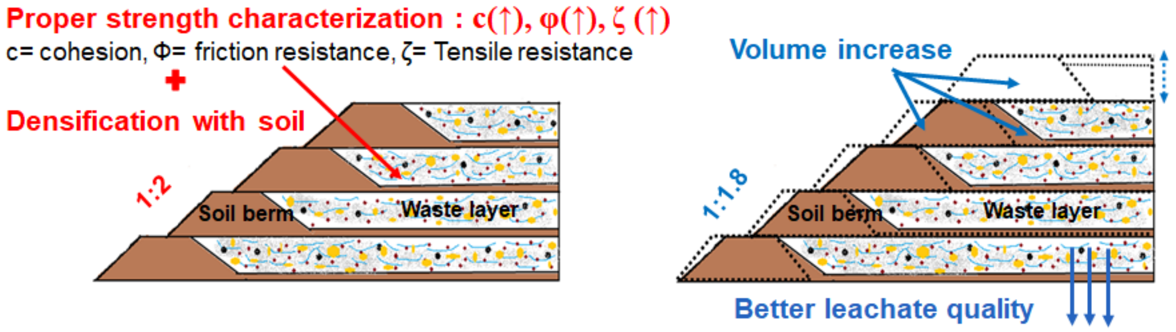
Chapter 1
Introduction

1.1 Background

Landfills are the final destinations of all kinds of waste generated around the world. In Japan, according to Waste Management and Public Cleansing Law, landfills are usually divided into three types- (i) Non-degradable waste landfill, (b) Municipal Solid Waste (MSW) and degradable waste landfill, and (c) Hazardous waste landfill. Inert waste landfills are the non-degradable waste landfill type landfills in Japan, where “inert” materials such as glasses, potteries, rocks, plastics and most of the construction and demolition wastes are landfilled. Presently, there are more than 1000 locations of inert waste landfill sites in Japan (Yamawaki et al. 2017). Although these inert waste landfills are regulatorily designated independently from the landfills for MSW landfills or controlled type landfills, the basic design for mechanical stability (or geotechnical design) just complies with the design instruction which exists for the MSW landfills. These design instructions are considered as too conservative for the inert waste landfills because the composition of the inert waste landfills is different than the municipal solid waste. Inert waste materials are important from geotechnical point of view (Monier et al. 2011); the concrete, rock etc. help in increasing the bearing capacity of the landfill and the fibrous fractions can act as reinforcement by providing tensile resistance to the landfill (Koelsch 2009; Zekkos et al. 2010a). Mechanical characterization and slope stability analysis are significant to design a strong and safe inert waste landfill with a steeper slope. Environmental safety of inert waste landfills from the leachate generated inside the landfills is also crucial to design a safe and sustainable landfill. Although inert waste should contain chemically inert materials, still there are some possibilities of the presence of biodegradable materials or contaminants in the inert waste, and there is a possibility of storage of leachate by the fibrous fractions inside the inert waste landfill, thus enhancing the risk of contamination. Figure 1.1 shows the concerns and solutions related to inert waste landfills. Waste fill stability, soil berm stability and leachate chemistry are the main concerns for inert waste landfills. Considering these issues, in this research, the mechanical properties, dynamic properties and leaching characteristics of the inert waste materials were studied. The relevant results were used to suggest the proportion and size of the components contributing to maximum strength and environmental safety. The usefulness of the experiments in various stages of landfilling was also discussed. The findings of this research are useful to design safer and steeper inert waste landfills.



(a) Concerns



(b) Solutions

Figure 1.1. Concerns and solutions related to inert waste landfills

1.2 Scope of this research

With the increase in population, waste generation is increasing day by day, and the landfills are filled at an alarming rate all over the world. The factors associated with social, economic, cultural, hydro-geological and seismic aspects make it difficult to set up new disposal sites. This problem generates the necessity of increasing the height of existing landfills within the initial footprint, thus resulting in steeper slopes. Steeper slopes can increase the waste storage capacity and reduce the burden of finding more land areas for the construction of new inert waste landfills. With mechanical and leaching characterization, strength, stability, and safety of the inert waste landfills can be evaluated, thus ensuring the possibility of reuse of the area to construct some new facilities after the closure of the landfill. Appropriate land use and reuse of inert waste landfills can reduce the negative impacts on the environment and encourage sustainability. This research assists to understand the mechanical properties, leaching properties, and dynamic behavior of inert waste landfills under earthquake condition. Previous researches on inert waste landfills are limited. It is because the inert waste landfills are still a new concept for many developing countries. Inert waste landfills are available in Japan, but they are still following the design instructions of municipal solid waste landfills. Therefore, even in the places where inert waste landfills exist, the design instructions may be too conservative in nature. The underestimation of mechanical characteristics of inert waste is a significant factor contributing to this conservativeness. Inert waste landfills show possibilities of having better strength than municipal solid waste landfills. The composition consisting of the construction and demolition waste with fibrous content has better geotechnical property and tensile resistance, which may improve the slope stability. For the mechanical characterization, in-situ data were collected, and different test apparatus were used for quick approximate analysis as well as precise analysis of strength parameters. The data can be used at three stages of design namely- planning, landfilling and future expansion. Understanding the mechanical properties of inert waste is significant to design new inert waste landfills and to increase the capacity of the existing landfills. From the dynamic analysis, the usefulness of the fibrous fractions already present in the inert waste in slope stability was analyzed. The actual landfill data collected during the mechanical characterization is significant not only for this research but also useful for future researchers. Leaching test was conducted to determine the safety from the storage of water by large fibrous fraction and to reduce the possibility of contamination. Lysimeter leaching tests were conducted using the inert waste collected from the landfill sites and those waste inside the lysimeter represented the actual field condition; therefore, a better idea about leachate behavior could be observed. For laboratory column leaching tests, moisture sensors were installed inside to find the exact moisture content stored above the plastics at some specific points inside the columns. The reuse of the excavated in-situ soil for sorption of heavy metals or other contaminants could also be confirmed through the leaching tests. The results obtained in this research will be useful for the researchers and engineers of all over the world to construct or expand inert waste landfills with safety and sustainability.

1.3 Research objectives

There are three main research objectives for this study. These are written below

(a) Study the effects of large fibrous fractions and density of inert waste on mechanical stability and contribution to a steeper design,

(b) Study the effects of large fibrous fractions and soil fractions on inert waste leachate properties, and

(c) Understand the dynamic behavior of landfills using centrifuge model test and FEM dynamic analysis to confirm the slope stability.

(a) Study the effects of large fibrous fractions and density of inert waste on mechanical stability and contribution to a steeper design.

The design instruction to inert waste landfills in Japan is considered as too conservative in terms of the mechanical stability, because inert wastes might probably have higher strength properties owing to the reinforcement effect of wastes contained (Monier et al. 2011). However, limitation of available knowledge does not allow to establish the design method specific to inert waste landfills. For example, among the waste components, granular fractions such as crushed concrete and rock help in increasing the bearing capacity of the landfill and fibrous fractions such as plastics and textiles can act for the reinforcement by providing tensile resistance to make a steeper slope for the inert waste landfill (Koelsch 2009; Takai et al. 2017). In this research, 14 locations of 4 inert waste landfills having different compositions were selected inside Japan and field tests such as composition analysis, basic physical properties, angle of repose, CASPOL impact value test, and in situ direct shear test were conducted at those locations. The percentage of each fraction of the inert waste has significant effect on the strength of landfills. Due to the variation in composition, the basic physical parameters and mechanical parameters of inert wastes may change. There are also some possibilities of changes in the physical characteristics as well as chemical characteristics in inert waste landfills with increase in age after reclamation (Chen et al. 2009). Therefore, variation in strength characteristics and in basic physical parameters (such as density, water content, percentage air voids etc.) with respect to different components and age after reclamation were observed in this study. The relationship between different strength parameters and typical values of strength parameters for inert waste landfills in Japan were also discussed. The laboratory direct shear test and triaxial test were also conducted to confirm and compare the shear behavior of the inert waste. Shear strength of inert waste for different fibrous content were determined to understand the effect of fibrous fractions on mechanical characteristics of inert waste. Strength parameters obtained from in-situ test and laboratory strength test are significant for slope stability analysis of the inert waste landfills.

(b) Study the effects of large fibrous fractions and soil fractions on inert waste leachate properties.

Leachate generation is a common phenomenon for all kinds of landfills. Various measures are taken by the landfill authorities to check the quality of the leachate as well as to maintain a better circulation of leachate. Although thorough inspections are conducted to avoid biodegradable waste materials in an inert waste landfill, due to human negligence or unavoidable circumstances, there may be a mixing of biodegradable waste with inert waste which may generate leachate inside an inert waste landfill. Inert waste landfills usually contain large fibrous fractions and there is a possibility of storage of leachate above these fibrous fractions inside the landfill. If there would be storage of leachate inside the landfill, then the stability of the landfill may decrease and the risk of contamination also increases with increase in time. Generally, inert waste landfills contain inert or chemically non-reactive wastes, which make inert waste landfills safer in terms of spreading the contaminations. Still, as already mentioned, sometimes biodegradable waste materials may enter in inert waste landfills. Moreover, heavy metals etc. may present in the construction and demolition waste or may naturally present in the soil found at the location of inert waste landfill. In this research, lysimeter leaching test, laboratory column leaching test, and laboratory batch leaching tests were performed to determine the leachate behavior or quality of the leachate produced in the inert waste collected from various landfill sites in Japan. Possibility of use of the soil excavated at the sites as a sorption layer was also studied. In lysimeter tests, drainage behavior of leachate was studied and change in parameters such as dissolved Total Organic Carbon (TOC), Total Nitrogen (T-N), Sulfate ion (SO_4^{2-}) with respect to the liquid-solid ratio (L/S) was observed for 5 sites of inert waste landfills. Sorption of toxic materials present in the leachate water by soil layer under the waste or soil mixed with waste was observed. Laboratory column leaching tests were conducted with columns having 2% and 10% fibrous content with soil layer to know leaching characteristics of inert waste materials due to variation in fibrous content. Moisture sensors were installed inside the columns to determine the storage of leachate due to variation in the fibrous fractions. Leachate behaviours for different depths of waste materials were also studied. Batch leaching test was conducted to have a quick understanding of the leachate quality of the inert waste materials used in laboratory column leaching test. The results obtained in leaching tests are necessary to design an environmentally safe and stable inert waste landfill.

(c) Understand the dynamic behavior of landfills using centrifuge model test and FEM dynamic analysis to confirm the slope stability.

In earthquake prone areas, dynamic analysis of inert waste landfills should be conducted before design. Seismic forces can affect the waste layer stability as well as the embankment slope stability. The tensile resistance offered by the fibrous fractions is one of the significant characteristics of the inert waste landfill materials. Taking a note on that, both experimental analysis and dynamic analysis were carried out to understand the slope failure behavior of landfills with and without fibers. Data were collected from different field tests on inert waste landfill sites such as in-situ density, water content measurement, SPT test, PS logging, repose angle test, and direct shear tests. Centrifuge model test was conducted to understand the slope failure behavior and to check the change in earth pressure on the landfill embankments. Due to size restriction of the centrifuge model, silica sand was chosen as the waste materials in the landfill models. The change in shear strength of the silica sand due to fibers mixing was also checked by laboratory constant volume and constant pressure direct shear test before using them in centrifuge model. In-situ density, water content, and shear wave velocity were used as input parameter for dynamic analysis. Dynamic analysis was first conducted to understand the slope failure behavior under strong earthquake and to verify the slope failure mechanism obtained by centrifuge test qualitatively. After verification of the centrifuge test results, parametric study (sensitivity analysis) was conducted considering some important factors of slope, composed by embankments and back landfills. Parametric study helps to provide some useful suggestions on the current design method for inert waste landfills. The analytical method used in this research is a common and conventional one so that it can be easily used by the practical engineers in their actual design. However, this method has several limitations in expressing the actual behavior of slope during earthquake.

1.4 Organization of this thesis

This thesis is divided into 7 numbers of chapters. The organization of the thesis comprises of total seven chapters is as shown in Figure 1.2.

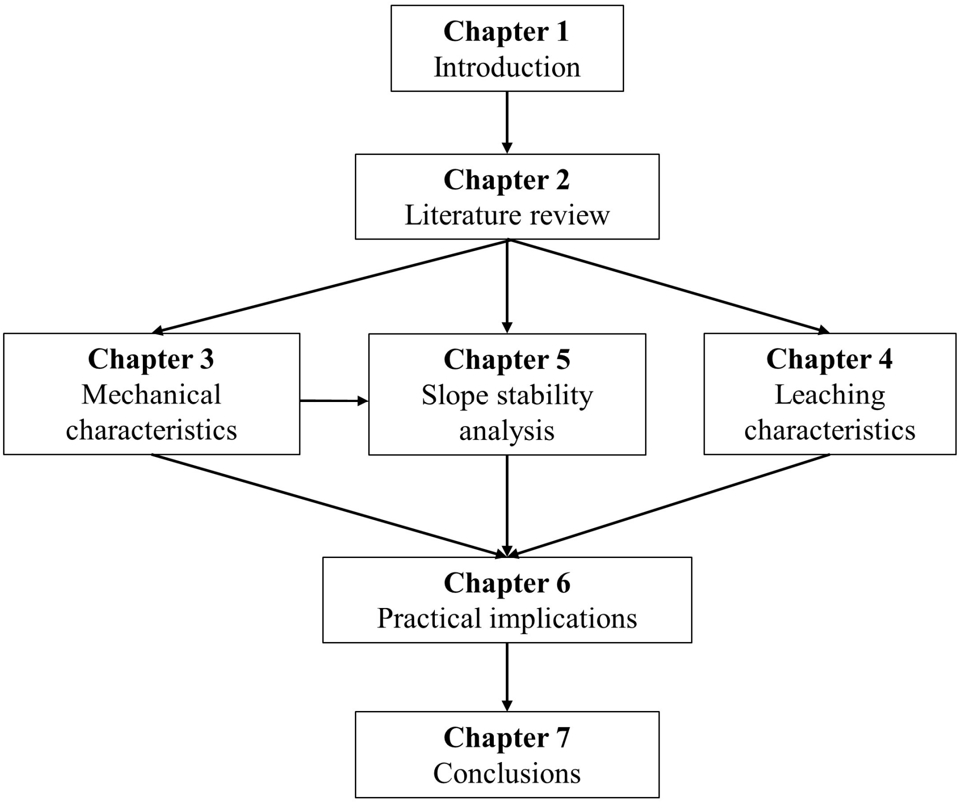


Figure 1.2 Organization of this thesis

Chapter 1: The background of the current research is described initially and subsequently scopes and research objectives are outlined in this chapter.

Chapter 2: The literature review pertinent to the present research is discussed in this chapter.

Chapter 3: Various in-situ and laboratory test methods for mechanical characterization of inert waste materials and their results are described in this chapter.

Chapter 4: Different leaching tests and their results are discussed to design a safe inert waste landfill with a better reclamation method.

Chapter 5: This chapter describes the slope stability analysis through centrifuge test models and FEM dynamic analysis. Determination of dynamic parameters from the in-situ tests are also described in this chapter.

Chapter 6: Practical implications of all the three main parts of this research namely- mechanical characterization, slope stability analysis, and leaching characterization are described in this chapter.

Chapter 7: This chapter summarizes the major findings of the current research and provides recommendations for the continuation of the present study.

Chapter 2

Literature review

2.1 General remarks

A review of pertinent literatures is the backbone of any kind of good research. A thorough understanding of what previous researchers have already studied and what is yet to be studied is important to start a productive research. Contrary to municipal solid waste landfill, inert waste landfill is a new concept to many countries. Therefore, a detailed study on various waste material's mechanical, dynamic, and leaching properties is needed so that the results can be utilized to design of a safe and sustainable inert waste landfill in three stages namely—planning, landfilling and future expansion. In this chapter, relevant literatures were selected from the past studies on mechanical characterization of different waste materials, leaching behavior of waste materials, slope stability analysis of landfills with fibrous fractions, and dynamic behavior of landfills under earthquake.

2.2 Mechanical characteristics of waste materials

To design economically, technically and environmentally sustainable inert waste landfills, detailed knowledge on inert waste mechanical characteristics are necessary (Powrie et al. 2006). Previously many researchers studied on the composition, physical properties, and geotechnical properties of municipal solid waste. Although the materials in MSW are different than the inert waste landfill materials, still there is one common characteristic between them, which is the heterogeneity of the waste. The strength characteristics measurement methods for heterogeneous municipal solid waste materials are useful for this study. Among the literatures on MSW, Zekkos et al. (2006, 2010b), Miyamoto et al. (2015) and Sebastian et al. (2019) studied the composition and physical characteristics of municipal solid waste.

Zekkos et al. (2010b) recommended a geotechnical characterization procedure which included four phases: phase 1—Collection and review of available information (e.g., waste processing and placement procedures, climatic conditions, and waste age), phase 2—Field characterization (stiffness, spatial variability, waste texture, color, temperature, composition, degradation, and moisture content as well as the presence of flowing or standing leachate in the boring or test pit), phase 3—Primary geotechnical characterization (waste separation into >20 mm fraction, with largely waste materials, and <20 mm fraction, with the soil-like material), and Phase 4—Secondary geotechnical characterization (moisture content and dry mass of individual components if needed). This geotechnical characterization procedure can also be followed for heterogeneous inert waste materials.

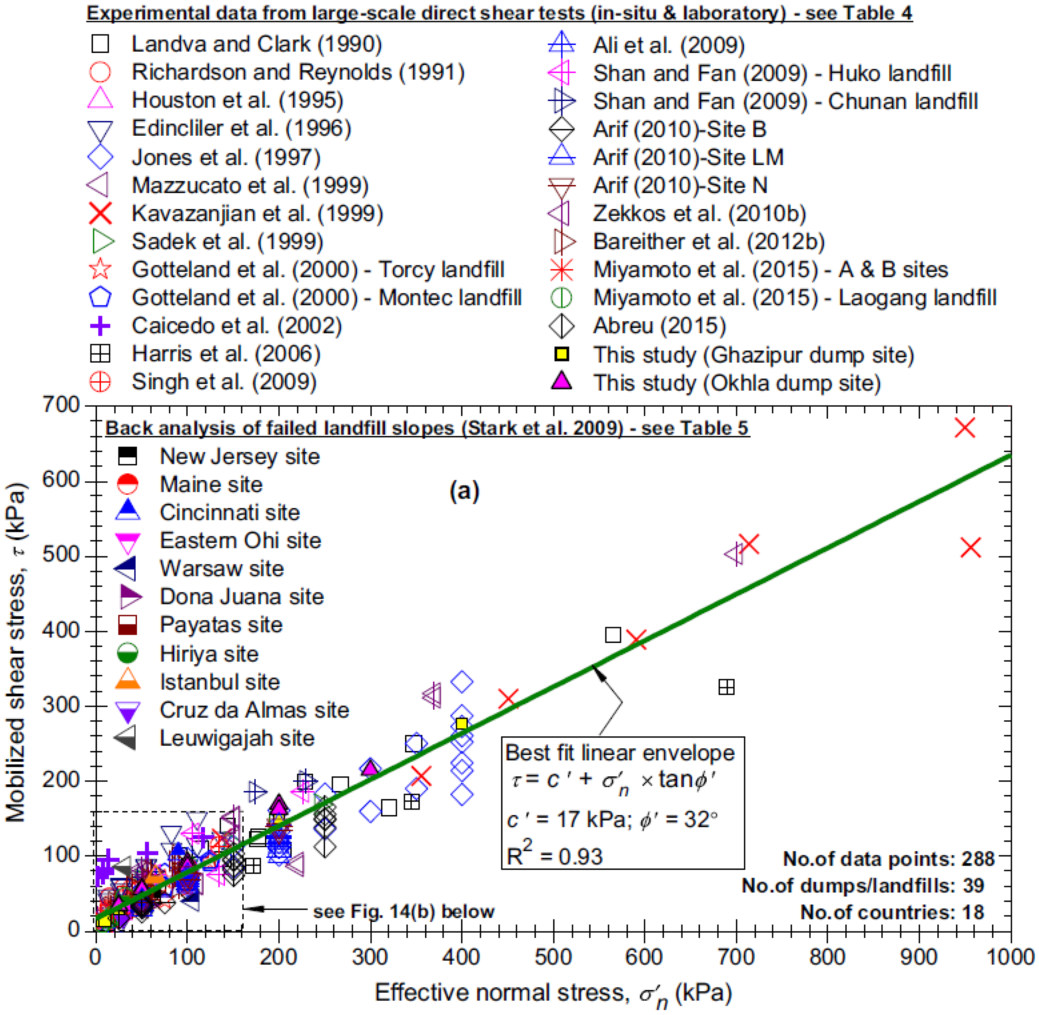


Figure 2.1 Shear strength data of MSW from back analysis of failed slopes and large-scale in-situ and laboratory direct shear tests (Ramaiah et al. 2017)

Dixon et al. (2005), Zekkos et al. (2013b), Ramaiah and Ramana (2014), and Reddy et al. (2009) studied on the mechanical characteristics of fresh municipal solid waste. Bray et al. (2009), Singh et al. (2009), Zekkos et al. (2010a), Ramaiah and Ramana (2017), and Ramaiah et al. (2016, 2017) conducted experiments to measure the shear strength of municipal solid waste. Ramaiah et al. (2017) collected MSW from two sites and conducted laboratory tests of compressibility and shear strength characterization with an automated large-scale direct shear

(DS) apparatus. The size of the DS box was 304.8 × 304.8 × 203.2 mm (length × width × height). They observed instantaneous compression which was completed within 40–50 min followed by a decreasing compression rate which was typical of a creep compression behavior. The compression ratio (C_c) varied between 0.13–0.16 and 0.11–0.17 for MSW in the test sites. Relatively low C_c was attributed to the relatively low percentages of compressible constituents such as plastics, rubber, and paper, coupled with high percentages of soil-like and gravel materials. With increasing age of MSW, the cohesion decreased and internal angle of friction increased for the waste at both the sites. Based on the study, for preliminary stability evaluation of MSW, a simple linear shear strength envelope, characterized by effective cohesion $c^{/} = 17$ kPa and effective internal angle of friction $\varphi^{/} = 32^{0}$, was proposed in case of unavailability of site-specific data. The data is useful for this study because they can be used to compare the strength characteristics of inert waste and municipal solid waste. Figure 2.1 shows the shear strength data of MSW from back analysis of failed slopes and large-scale in-situ and laboratory direct shear tests conducted in Ramaiah et al. (2017).

Reddy et al. (2011, 2015) studied on the change on mechanical properties due to degradation. They used five samples with degree of decomposition of 0, 50, 53, 70, and 86%. With increase in biodegradation, cohesion increased and internal friction angle decreased. However, these findings were showing opposite trend than the previous studies by Langer (2005); Hossain (2002); Howland and Landva (1992). Therefore, analysis of the change in strength parameters of inert wastes with respect to different composition and age after reclamation will be useful for the future researchers. As one of the main components in inert waste is fibrous content, literatures on the change in strength characteristics of soil or waste due to fibre reinforcement are also handy for this study. Consoli et al. (2010), Zekkos et al. (2013a), Chebet et al. (2014), Festugato et al. (2017, 2018), and Shirvani et al. (2019) noticed improvement in shear strength of soil and waste due to fiber reinforcement.

Studies related to strength characterization of construction and demolition (C&D) waste or inert waste are fewer in numbers because only a few countries in the world have regulated inert waste landfills to dispose C&D waste or inert waste. Landfills specific for inert wastes, or inert waste landfills, have been implemented in European Union (EU), Japan, and probably other countries. Among the available few literatures, the landfill directive for the Environmental Permitting

(England and Wales) Regulations (2010) mentions that inert wastes can be used for redevelopment/restoration and filling-in work, or for construction. Saberian et al. (2018) and studied about the improvement of the mechanical characteristics of construction and demolition waste using accelerated carbonation. Moreira et al. (2019) measured different strength properties of soil mixed with roof tiles. Omine et al. (2014) studied the relationships between shear stress and shear displacement of solid waste materials (SWM) at 2 m and 4 m below the ground level as shown in Figure 2.2. Shear tests at the site of GL-2m and GL-4m were conducted under three normal stresses of 5.14, 10.9, 16.35 kN/m^2 and a normal stress of 10.9 kN/m^2, respectively. The shear stress of solid waste material increased linearly with increase of shear displacement and normal stress. A peak shear stress did not appear. For the same normal stress of 10.9 kN/m^2, shear stress and vertical displacement of SWM at the site of GL-4m were greater than those at the site of GL-2m at the same shear displacement. These results indicated that shear property of SWM depends on stress history.

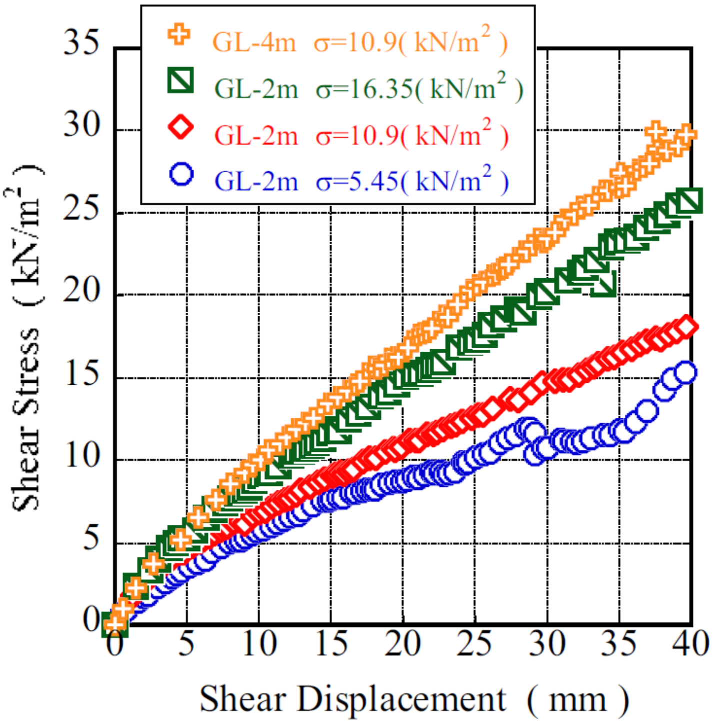


Figure 2.2 Shear stress vs shear displacement (Omine et al. 2014)

Omine et al. (2015) and Miyamoto et al. (2015) studied on strength characteristics of inert waste materials and concluded that the tensile resistance from fibrous content in the waste plays a significant role to increase the factor of safety in case of slope stability. They proposed the angle of repose test as a simple on-site test method and confirmed to be a good indicator for slope stability assessment. They also suggested that landfills which have higher water content have considerably poorer slope stability. Yamawaki et al. (2017) concluded that the slope stability is sufficiently higher for typical composition of inert waste, if fibrous materials do not contain excess water.

2.3 Leaching characteristics of waste materials

The first European Directive on surface water was published in 1975 (Surface water 1975/440/EEC), after which appropriate treatment" was imposed on the industrial effluents (Wiszniowski et al. 2006). Consequently, pre-treatment of landfill effluents was also needed to meet the quality standards. To determine the procedure of treatment, first it is necessary to determine the contaminants present in the landfills. Many studies had been made on the leachate qualities of municipal solid waste landfills as those were the common landfills present everywhere.

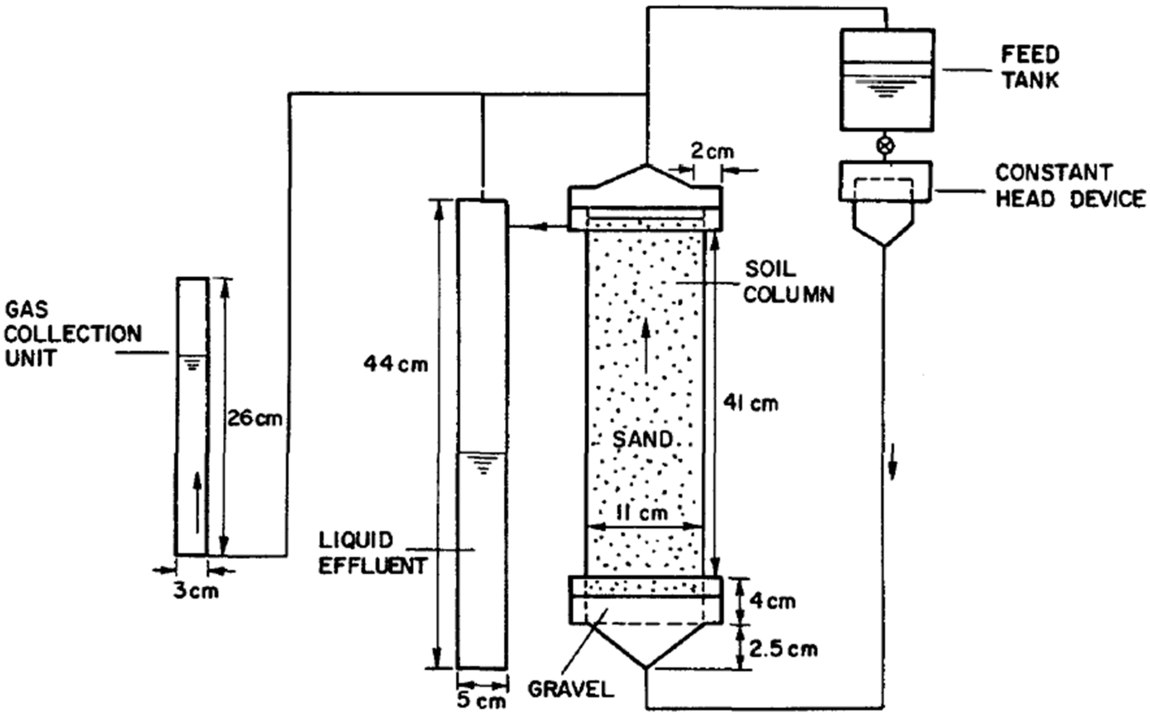


Figure 2.3 Schematic diagram of soil columns (Farqdhar and Sykes, 1982)

Farqdhar and Sykes (1982) stated that in many case, concentration of organic matters in municipal solid waste landfill leachate are quite high. They investigated the types of organic matters, extent and rate of organic matter reduction, and factors affecting them. The liquid was prepared by adding water with residential solid waste in a laboratory lysimeter under positive head upflow saturated condition. The biological culture developed after daily addition of leachate to two completely mixed reactors (CMR) under anaerobic conditions was utilized for the soil column experiment as shown in Figure 2.3. The study indicated that considerable amount of leachate organic matter in soil can be removed through the application of microorganisms. Soil acid neutralizing capacity, sorption capacity particularly for biologically resistant compounds, and fluid flow related properties play significant role in removal of organic matter.

The 11th Report of the Royal Commission on Environmental Pollution (1985) assessed the problems related to waste disposal and management. Combination of burnable ingredients such as paper and timber, other organic residues, plastic, glass, ash, clinker and ferrous metal produce domestic waste. Domestic and industrial wastes are mixed often and toxic metals present in them in varying concentrations lead to isolated packets of hazardous materials that contain phenols, cyanides and asbestos. Ninety percent of such refuse is dumped in landfill sites in urban areas and rest is used in future development (housing etc.). Toxic and gaseous mixtures of methane and other gases are produced by the microbial decay within the landfill which can also be explosive, thus presenting potential fire hazard. An elevated concentration of sulphate, sulphide and chloride present in wastes is aggressive to building materials. The leachate can be exceedingly acidic and may contain soluble toxic constituents other than metallic components which can contaminate the groundwater. Nasty odor generated from landfill is another problem to be considered.

According to Thornton (1990), although most of the building materials are comparatively inert; heavy metals (including lead from paint), gypsum and asbestos used in old buildings and industrial premises can result in contamination of soil. Scott (1995) identified four factors affecting the quantity and composition of the leachate. The factors were- waste types, disposal methods, construction and age of the landfill, and climate and seasonal effects. He also commented that the leachate must be treated prior to discharge into surface waters. To select the most appropriate treatment system, one should be careful about (a) the composition of the leachate at source, (b) the required discharge standard required by the regulating authority, and

(c) the anticipated flowrate that will require treatment. According to Van der Sloot (1996), leaching behaviour of bulk waste materials are more consistent in comparison to single extraction tests. It is because the sensitivity to some specific leaching controlling factor are unrecognized. The minor change in pH or redox go unnoted in case of bulk waste materials which may lead to differences in order of magnitudes.

In Delay et al. (2006), the results from column test and lysimeter test were presented and compared for better-quality environmental risk assessment as shown in Figure 2.4. The results showed that for most elements, there was a good agreement between the leaching behaviour determined with lysimeter units and column units used in the laboratory. Therefore, due to lower time and system requirements of laboratory column units, they can be used as a practicable tool for waste management authority. They also recommended to conduct batch test and soil saturation extract test as preliminary test, before the detailed and time resolved column test.

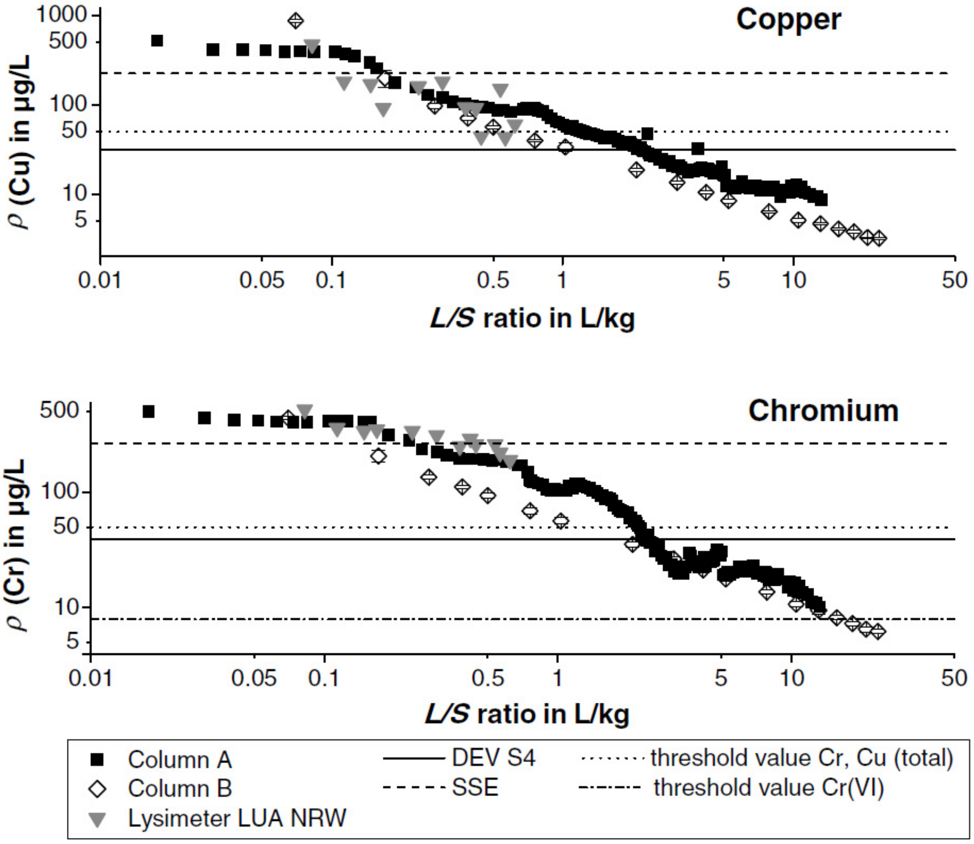


Figure 2.4 Comparison of leaching behaviour of copper and chromium in the laboratory column and the lysimeter leaching tests (Delay et al. 2006)

Kalbe et al. (2007) evaluated the reproducibility of column percolation and found that comparative column percolation tests demonstrated good reproducibility of results for organic, inorganic and accompanying chemicals even though the dimensions of the column used were different. From these results it can be concluded that by applying strict specifications for the investigational procedure reproducible result can be achieved.

Sormunen (2008) monitored a Finnish MSW landfill in Lahti, Kujala operating for about 50 years and characterized the internal leachate quality. The leachate was monitored with 14 operating wells over a 2-year period for COD, BOD, TKN, NH_4–N, Cl, pH and electric conductivity. This study provided information about horizontal and vertical variation of leachate as well as effects of leachate recirculation on leachate quality. The monitoring wells presented high horizontal and vertical variability in leachate quality which implies that age and properties of waste, local conditions (e.g., water table) and degradation and dilution processes ensure a striking influence on the localized leachate quality. The mean COD values (642–8037 mg/L) and mean BOD/COD ratios (0.08–0.17) obtained from monitoring shafts represented characteristic methanogenic degradation phase values. The leachate in the monitoring well were more concentrated than the recirculated leachate. The influence of leachate circulation on leachate quality seemed negligible and inexpedient to separate from other factors in the landfill. The concentration values obtained for different contaminants in inert waste leachate can be compared with these values of municipal solid waste landfills.

Krüger et al. (2011) studied the influence of different column filling heights (12.5–50 cm) on the release of polycyclic aromatic hydrocarbons (PAH) from soil. The effect of varying contact times (2.5–16 h) on the release of chromium from C&D waste and MSW incineration bottom ash were also observed. Results showed that medium column heights four times the inner diameter of the column is a reasonable for lower biodegradation. The release of chromium was only slightly affected by the contact time, which provides justification for a shorter contact time.

Galvin et al. 2012, carried out a comparison of batch leaching tests and influence of pH on the release of metals from construction and demolition wastes. The leaching tests performed were: The Dutch leaching test NEN 7341, 1994 and The European standard UNE-EN 12457-3, 2002 simulate extreme conditions to obtain a high leachability of the product. The comparison showed that the highest level of contamination was obtained experimentally by the Dutch procedure after 6 h of stirring at pH of 4. For all analysed elements, a greater release was obtained at low pH values. Consequently, the highest levels were obtained by the Dutch availability test and the leached levels were at their maxima due to the degradation of the paste. The results proved that pH was the most relevant factor on the assessment of the differences between leaching methods due to its strong control on the pollutant release. According to the data, high amount of pollutants was removed by the Dutch test (at L/S of 50 L/kg) due to the easily separation from the material to the aqueous phase. Lower levels were registered by the European standard performed at L/S of 2 and L/S of 10 L/kg.

In Asakura 2015, a limit value for gypsum ($CaSO_4$) was suggested for the suppression of hydrogen sulfide (H_2S) generation at an inert solid waste landfill site. According to that study, in order to suppress H_2S generation to less than 1000 mg/L, SO_4^{2-} concentration should be less than approximately 50 mg-SO_4^{2-} /L. Or else, if SO_4 concentration is high, TOC concentration should be less than approximately 200 mg-C/L. The limit value for SO_4^{2-} in the ground in order to suppress the generation of 2000 mg/L H_2S is 60 mg-SO_4^{2-} /kg with 0.011 wt% as gypsum dihydrate.

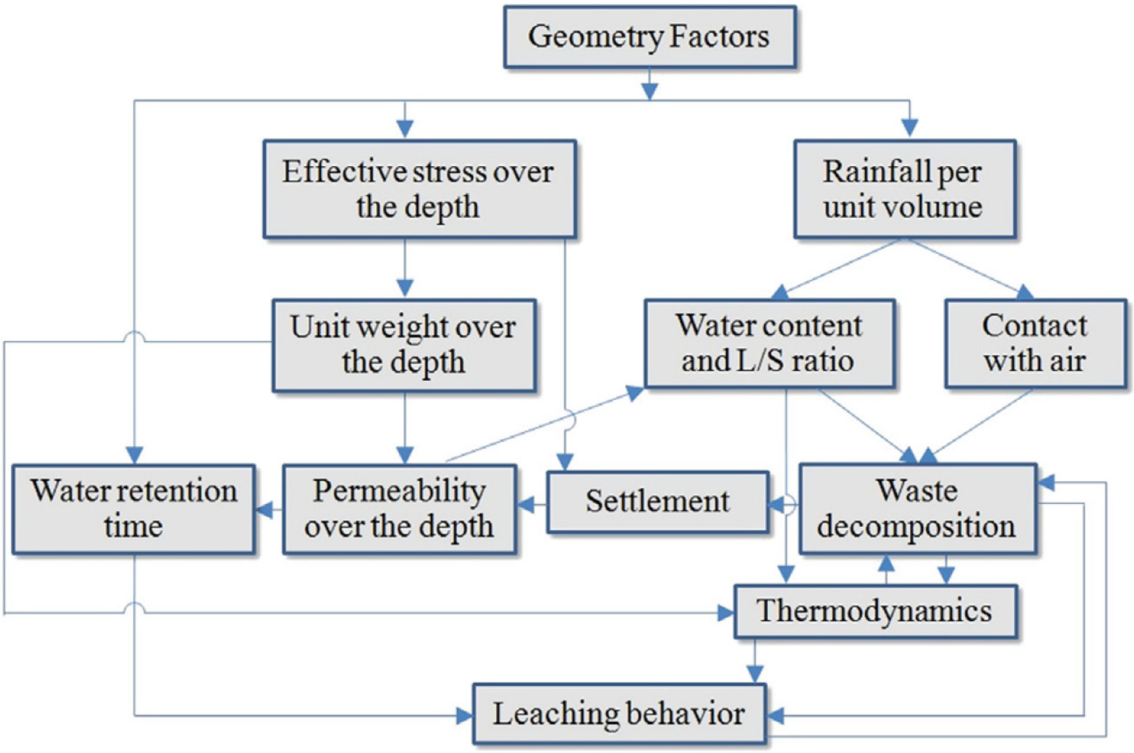


Figure 2.5 The effect of geometrical factors on leaching behavior and waste decomposition (Qiang et al. 2015)

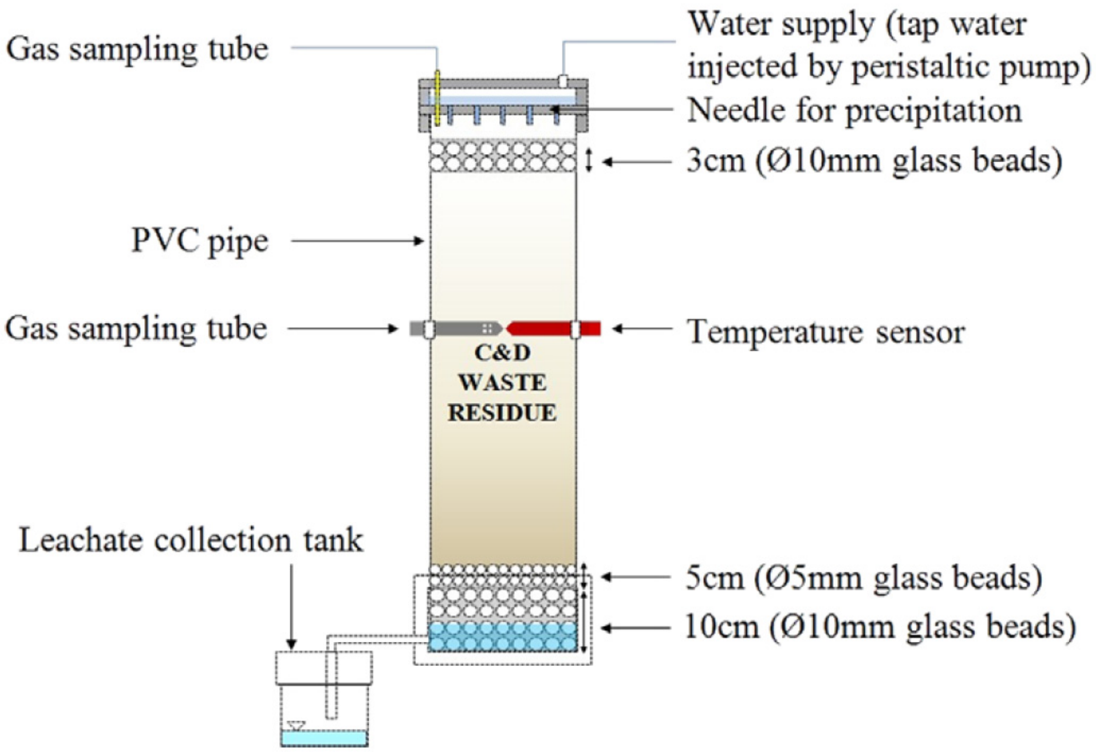


Figure 2.6 Schematic diagram of lysimeter (Qiang et al. 2015)

Qiang et al. (2015) simulated the environmental conditions of landfill with construction and demolition waste using lysimeter as shown in Figure 2.5 and 2.6. The change in physical and thermodynamic characteristics of landfill, the waste decomposition rates and leaching behaviour with respect to the various geometrical characteristics (e.g. height/width ratio and height) were observed. For the leaching test, high alkalinity of the sample was observed due to the presence of CaO, originating from cement or other construction materials. The inorganic ion concentration did not vary according to the particle size. However, the pH and EC were higher in case of smaller particles. This can be attributed to the particle size of soluble content, as in general, soluble content is mostly exists in the form of powder or smaller particle size. The lysimeter test results revealed that preferential and sidewall flows can easily occur with high H/W ratio. For lysimeters with height less than 0.7 m, the filtration water could completely flush. If the height was increased, the leaching behaviour was lowered due to the pressure on the bottom waste particles exerted by the greater upper loading. Heavy metals were also leached out from lysimeter test. This phenomenon was explained by three factors; first the lacking of clay minerals in the C&D waste which contributes in adsorption of heavy metals; second microbial activity and third amphoteric character of heavy metals which was responsible for parabolic concentration curves of heavy metals as a function of pH value. Moreover, emission behaviour some inorganic ions suggested that the leaching behaviour can be affected by microbial activity which should not be neglected in landfill research activities. The results obtained are important for this study because the maximum part of the inert waste consists of construction and demolition waste.

Butera et al. (2015) conducted leaching test on construction and demolition waste with up flow column test and down flow lysimeter test. Column test were meant to provide basic leaching characteristics whereas lysimeter test were intended to mimic actual field conditions. For the leaching data, there were overall similarities observed among the samples. In the study, considerable differences in the materials for different samples were noticed. In general, differences were within a factor of 2; however, for a range of elements, significant differences were observed in terms of cumulative release at L/S 10 L/kg TS: P, Ba, Mg and Zn (lower releases in up-flow columns compared to lysimeters), and Pb (higher releases in up-flow columns compared to lysimeters). More differences between the two tests were associated with the early leaching below L/S 5 L/kg TS: Al, As, Ba, Cd, Cu, DOC, Mg, Mn, Ni, P, Pb, Sb, Se, Si and Zn. The pH in the initial leachate data were found higher in case of column leaching than that of lysimeter test. Crushing of materials in case of column leaching may be the reason behind this phenomenon since crushing exposes new unweathered surface materials to less carbonated materials. Furthermore, non-equilibrium conditions in the lysimeters, due to the larger particle size, preferential flows and absence of a pre-equilibration phase, might also cause the detected differences. Calculated mineral saturation indices showed that according to sample and percolation test type: alumina ferric oxide monosulphate (AFm), portlandite, solid solutions of Ba/Ca/Sr sulphate and chromate, gypsum, amorphous silica, leaching could be controlled by different phases. Minerals such as portlandite were modelled as more likely in up-flow columns, while phases such as amorphous silica were closer to equilibrium in the lysimeters. Butera et al. 2015 concluded that although the up-flow column test is useful for comparison and standardized test, however the releases in the column test and lysimeter test may significantly vary. Moreover, to estimate the initial concentrations for risk assessment, the lysimeter results can be used for the validation.

In Roque et al. 2016, leachability of Construction and Demolition Recycled Materials (C&DRM) in compliance (batch test) and basic characterization (lysimeter test) leach tests were observed to evaluate the environmental hazardous of C&DRM. The results in the batch test, suggested the feasibility of using the studied recycled aggregates in the construction of road pavement layers, as the levels of substances released were far below the leaching limit values for waste acceptable at landfill for inert waste. Regarding the release of the substances in the batch and lysimeter tests, it was observed that the concentration of chloride and sulphate were lower in the batch test than in the lysimeter test, but with the dissolved organic carbon, the opposite occurs. Therefore, conservativeness of the methods could not be concluded from this result.

2.4 Slope stability analysis/dynamic behavior of landfills

Centrifuge testing is a prominent method to investigate behavior of soil by means of model tests. As landfills are large scale geo-structures, it is time consuming and uneconomical to conduct full scale experiments for the purpose of geotechnical analysis. In centrifuge tests, small scale model tests can be performed at a stress condition identical or equivalent to full scale prototype by increasing the value of gravitational acceleration (g); thus, eliminating the disadvantages of full-scale experiments (Wood 2004). Moreover, dynamic centrifuge model test can help in investing the response of soil under the action of dynamic load such as earthquake (Brennan et al. 2005). Examples of centrifuge tests on soil slopes (Cheney and Oskoorouchi 1982; Kim and Ko 1982; Zornberg et al. 1997; Nova-Roessig 2006) and landfills (Thusyanthan et al. 2006 and Chen et al. 2017) can be found to understand static and dynamic response of soil and landfill slopes respectively.

Dynamic analysis is another alternative to understand the dynamic response of soil, which is influenced by dynamic properties of soil. The ground response analysis can be one, two or three dimensional. Sloping surfaces are often treated as two-dimensional plane strain problems. Such problems can be analysed using dynamic finite-element analysis, shear beam approach and layered inelastic shear beam approach (linear or non-linear approach) (Krammer 1996). Rathje and Bray (2000) conducted 1D and 2D finite element dynamic response analyses to evaluate the seismic response of solid-waste landfill and proposed a simplified procedure for scaling 1D results to account for 2D topographic amplification and cover slope averaging.

The shear strength of soils or waste materials are directly related to the slope stability of the waste landfills or soil embankments. The internal friction angle or repose angle are the maximum slope of any type of heap before slope failure and these parameters usually depend on the composition of the waste. Previously many researchers studied on shear strength parameters of municipal solid waste landfill. Zekkos et al. (2011) studied the dynamic properties such as shear wave velocity, Possion's ratio etc. of municipal solid waste by conducting in-situ field tests. The numbers of studies related to shear strength or dynamic parameters of inert waste are fewer as inert waste landfills are not common in many countries. However, recently many developing countries such as India, Vietnam etc. are focusing on the proper disposal of construction and demolition wastes as these countries producing a huge amount of construction and demolition waste due to recent growth in country's infrastructures.

The inert waste landfills are present in Japan, but studies on the shear strength characteristics on inert waste started recently and are fewer in number (Omine et al. 2014, 2015; Miyamoto et al. 2015 and Yamawaki et al. 2017). Omine et al. (2011) conducted earth pressure test on slopes of inert waste with and without fiber as shown in Figure 2.7 They made three specimens – the first specimen was a slope of granite soil or commonly known as masado, the second was a slope of inert waste, and the third was a slope of inert waste divided into two equal parts. The both cases with inert waste showed less earth pressure than masado and the divided inert waste in 3rd specimen showed more earth pressure than the whole inert waste in the 2nd specimen. The tensile resistance of the fibrous content combined the waste materials together contributing to better slope stability, but in case of divided inert waste, the tensile resistance could develop well. Similar results were observed when Tanaka et al. (2016) conducted shaking table test to evaluate seismic earth pressure of inert waste materials and they compared the results with toyoura sand as shown in Figure 2.8. The results showed that the earth pressure of waste materials with fiber was lesser than the toyoura sand without fiber.

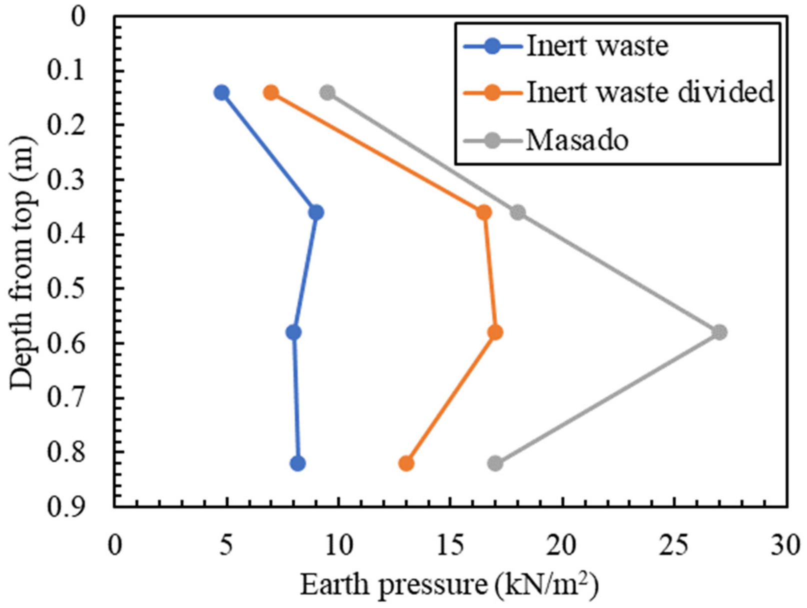


Figure 2.7 Earth pressure test on waste materials and masado (Omine et al. 2011)

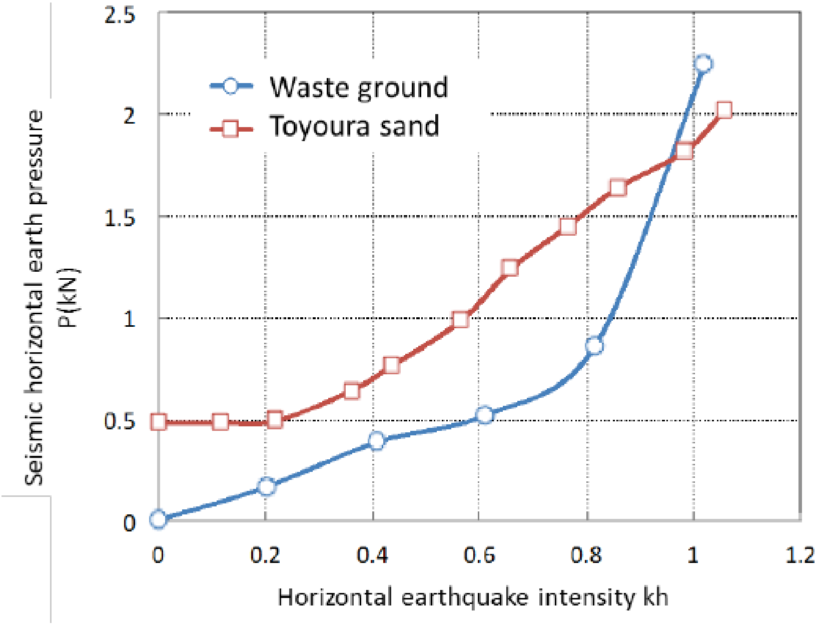


Figure 2.8 Shaking table test on inert waste (Tanaka et al. 2016)

Anderson and Kavazanjian (1995) summarized the seismic performance of MSW landfills across the United States. It was reported that the performance of MSW landfill in case of earthquake is generally good. They mentioned that usual effects of earthquakes on MSW landfills include and movement of downslope of the cover soils and interference to landfill gas collection systems. A performance documentation was created which consists of landfills in the epicentral location of 7 magnitude earthquakes with steep slopes as 2H: 1 V with heights of around 90 m. However, only three of those landfills have geosynthetic liner and were subjected to high ground motion in excess of 0.3g. They recorded that one of them has experienced damage in the geomembrane. They stated that caution should be adopted in the design of geosynthetic liners for MSW landfills.

Bray et al. (1995) adopted results from the wave transmission equations in one-dimension to evaluate the seismic stability of landfills. They reported that seismic stability of landfill is greatly influenced by the dynamic properties and height of the landfill and height of the landfill, and the behavior of the design bedrock movement such as intensity, excitation frequency and duration of excitation. They concluded from several case studies that when the fundamental period of the landfill is at least two times larger than the design bedrocks predominant period, the maximum horizontal acceleration will be lower than half of bedrock's maximum induced horizontal acceleration as shown in Figure 2.9.

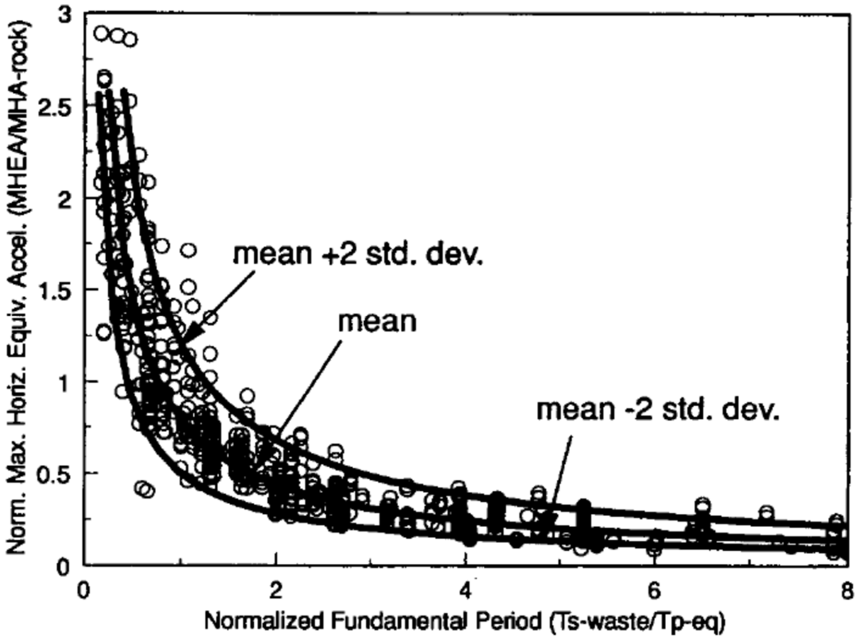


Figure 2.9 Variation of normalized maximum horizontal acceleration with normalized fundamental period of landfill (Bray et al. 1995)

Ling and Leshchinsky (1997) developed equations for evaluating the seismic stability and permanent displacement of landfill liner subjected to static and seismic loadings. They reported that finite slope analysis has a significant influence on the stability of landfill liner in comparison to infinite slope analysis. The geometry of the slope, sliding coefficient of soil-geomembrane assembly, and their adhesion affect the stability of the landfill. It was also stated that stability and permanent deformation of the system is affected by the length and thickness of the cover.

Bray and Rathje (1998) investigated the behavior of MSW landfills subjected to high levels of earthquake motions by using non-linear dynamic analysis program. The results obtained from dynamic analysis demonstrated that dynamic performance of MSW landfills is significantly influenced by the wastes' dynamic properties, height of the fill, site condition, input motion of the bedrock. The maximum horizontal equivalent acceleration (MHEA) is greatly dependent on the mean period and maximum horizontal acceleration of the input bedrock motion. It was also reported that the amount of permanent deformation induced by earthquake shaking is affected by ratio called k_y/k_{max}, where k_y is the yield acceleration and k_{max} is the MHEA/g. The permanent displacement is also influenced by intensity, input frequency, period of motion and soil properties of the foundation.

Zekkos et al. (2008) conducted large scale cyclic loading tests on MSW collected from San Francisco bay locations. The parameters that were measured were the small strain shear modulus (G_{max}), shear modulus degradation (G/G_{max}) with increased shear strain and the material damping ratios. Their experimental results revealed that the waste composition has the most dominating influence on the dynamic responses of MSW landfills. As the quantity of fibrous materials of sizes greater than 20 mm size increases, the G_{max} reduces, G/G_{max} curves move to the right and the damping ratio decreases substantially at large shear strains. The factors that play a greater role on the G_{max} are the confining stress, density, and duration of confinement, but frequency has a minor influence on G_{max}. Furthermore, they mentioned that G/G_{max} curves are greatly affected by waste composition and confining stress level.

Bray et al. (2008) performed large scale direct shear, triaxial and simple shear tests on MSW to develop a framework for shear strength. They revealed that direct shear test is appropriate to evaluate the shear strength of MSW along the weakest plane. The weakest plane is the direction parallel to the preferred orientation of the large size fibers. They also compiled a database of large number of direct shear tests conducted on MSW and stated that the cohesion and friction angle obtained from a direct shear tests are 15 kPa and 36° respectively, with friction angle values dropping 5° every log cycle increase in vertical stress. The friction angle values increase for other methods of shearing i.e. triaxial compression tests.

Alidoust et al. (2018) performed cyclic triaxial tests on MSW collected from Tehran to evaluate the effect of fibrous content on the dynamic properties of the MSW. They witnessed an improved elastic response of the MSW with the increase in fiber content. They stated that the G/G_{max} curves shift to the right with the increase in fiber content, although little influence on the damping behavior was observed.

2.5 Summary

This chapter summarizes various relevant literature related to the mechanical and leaching characterization of waste materials and slope stability analysis of waste landfills. Basic physical properties, shear strength parameters, and study related to degradation of waste materials due to presence of organic materials were some of the significant topics studied by many researchers. The studies also shed a light on various factors effecting leachate behavior of soil or waste, which are useful for safe reclamation of inert waste. Previous studies on leaching characteristics of construction and demolition waste are useful for this study. The data of various strength properties and dynamic properties related to slope stability analysis and the behavior of landfill slopes under dynamic conditions are significant for a better slope design of inert waste landfills.

Chapter 3

Physical and Mechanical characterization

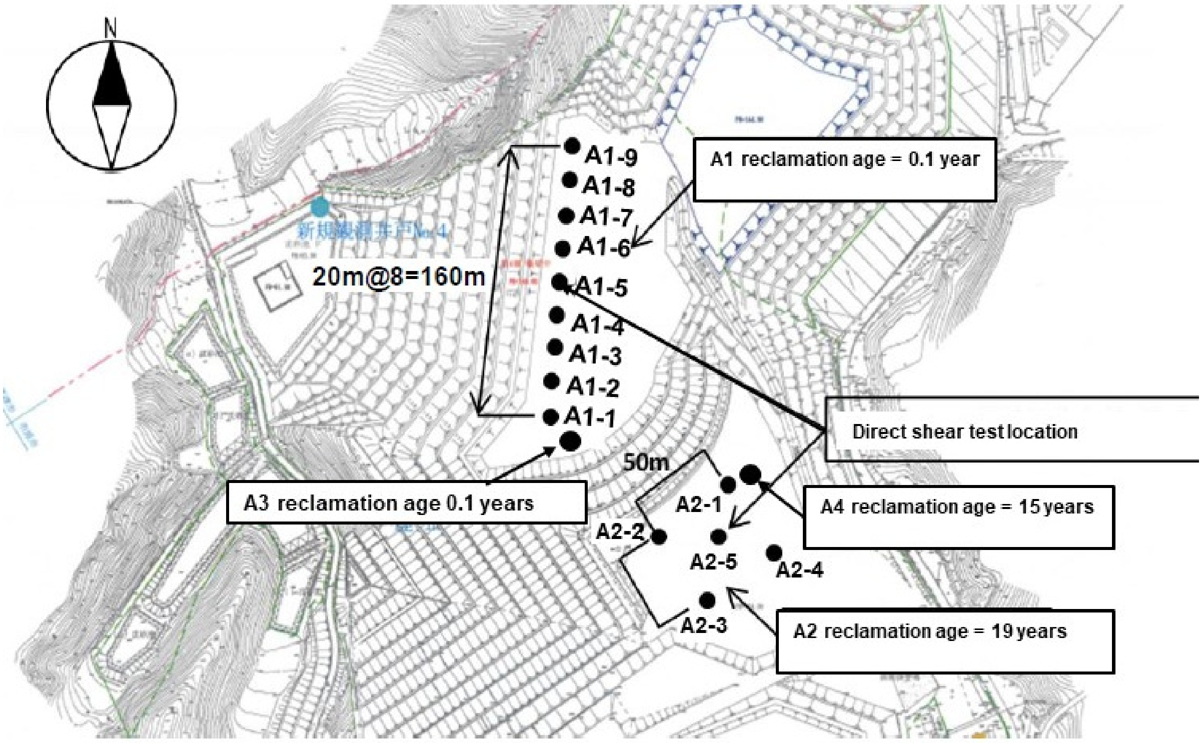
3.1 General remarks

Mechanical characterization of inert waste through composition analysis, basic physical parameters, and strength parameters is significant to design a strong and safe inert waste landfill with a steeper slope. The shortage of land areas in Japan demands a steeper slope, future expansion or reuse of these landfills, and to fulfill these demands, the mechanical properties of the inert waste materials are vital during the design stage. Composition analysis helps to understand the ratio of different materials present in the waste which in turn may have significant effect in the mechanical characterization. Basic physical properties are significant, as they provide the idea of the in-situ condition of the inert waste materials. If the basic physical parameters of the landfills are known, then the strength characteristics with respect to each parameter can be thoroughly understood and better reclamation method can be obtained. The shear strength parameters of inert waste are highly dependent on the composition and basic physical properties. Among the other materials present in the composition of inert waste materials, fibrous fractions showed a positive effect due to its tensile resistance property. Koelsch (2009), Omine et al. (2014), and Yamawaki et al. (2017) previously observed this type of tensile resistance in different solid waste (MSW) materials containing fibrous fractions. In this research, in-situ tests were conducted to determine the physical and shear strength parameters of inert waste landfills. Laboratory direct shear test and triaxial test were also conducted to observe the effect of fibrous fractions on the basic physical properties and shear strength parameters of the inert waste materials.

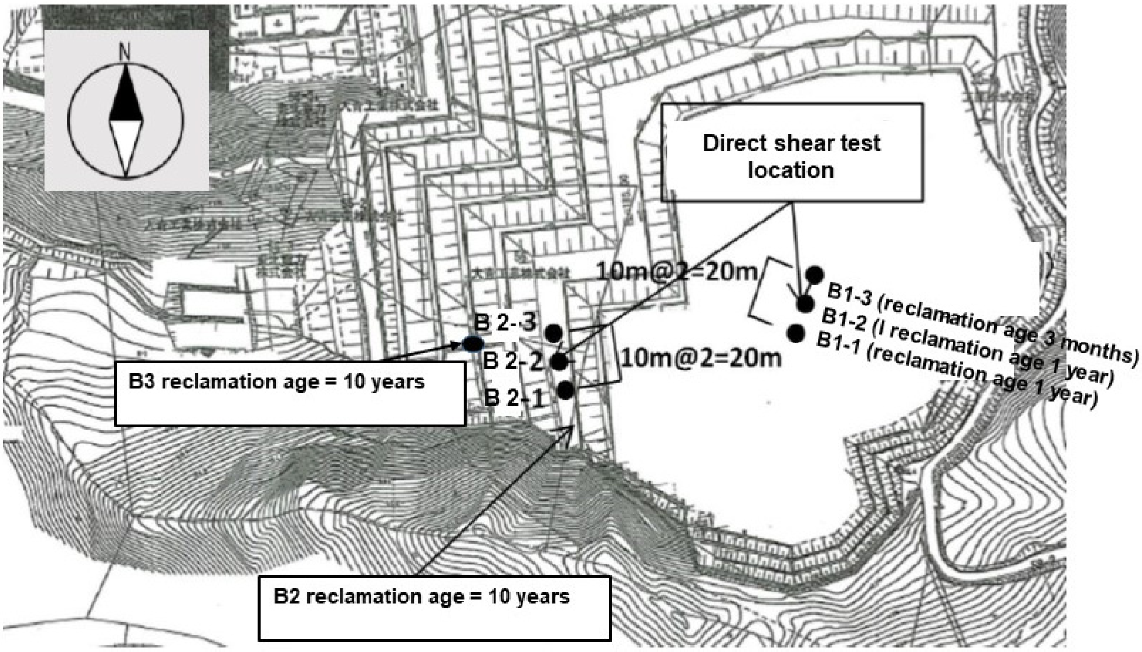
3.2 In-situ test

3.2.1 Methods and materials

Field tests such as composition analysis, basic physical properties, angle of repose, CASPOL impact value test, and in situ direct shear test were conducted at 14 locations of 4 inert waste landfills inside Japan. The 4 inert waste landfills are A, B, C, and D; where A and D are situated in Chiba, B is situated in Miyagi, and C is situated in Aichi prefecture. The locations were named as A1 to A4, B1 to B3, C1 to C5, and D1 to D2. The landfills with different locations are shown in Figure 3.1. At each location, 3-10 points at distances of 10-20 m were taken to determine physical and mechanical characteristics of inert waste.

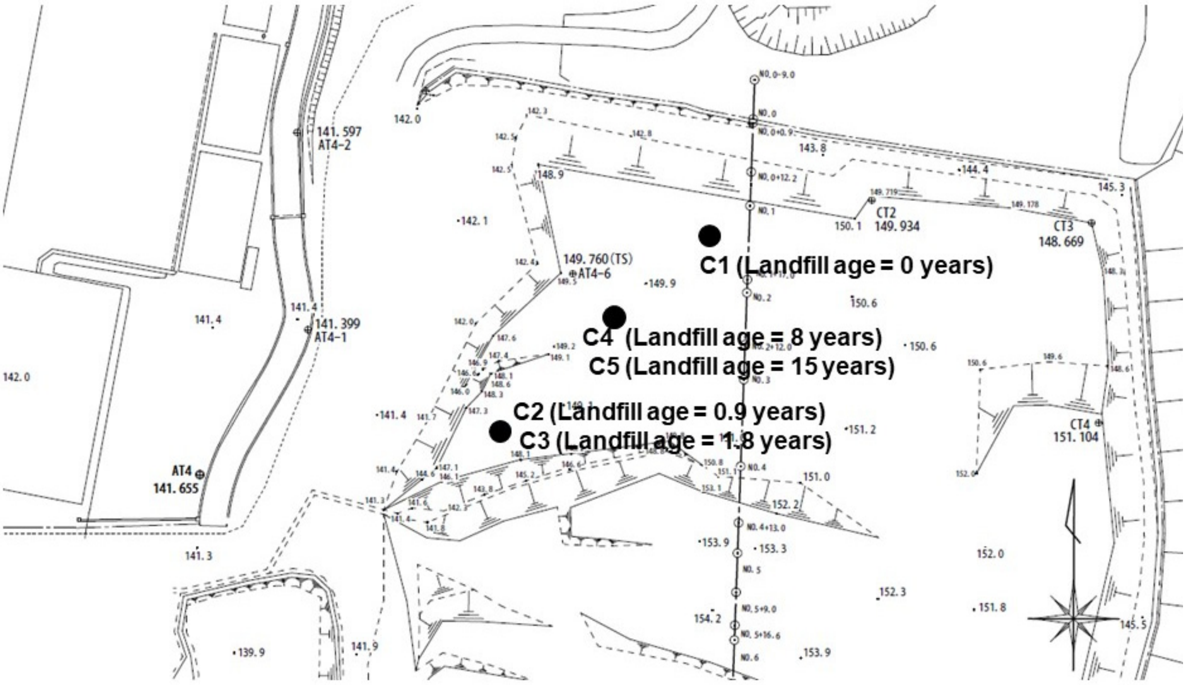


(a) Chiba landfill A

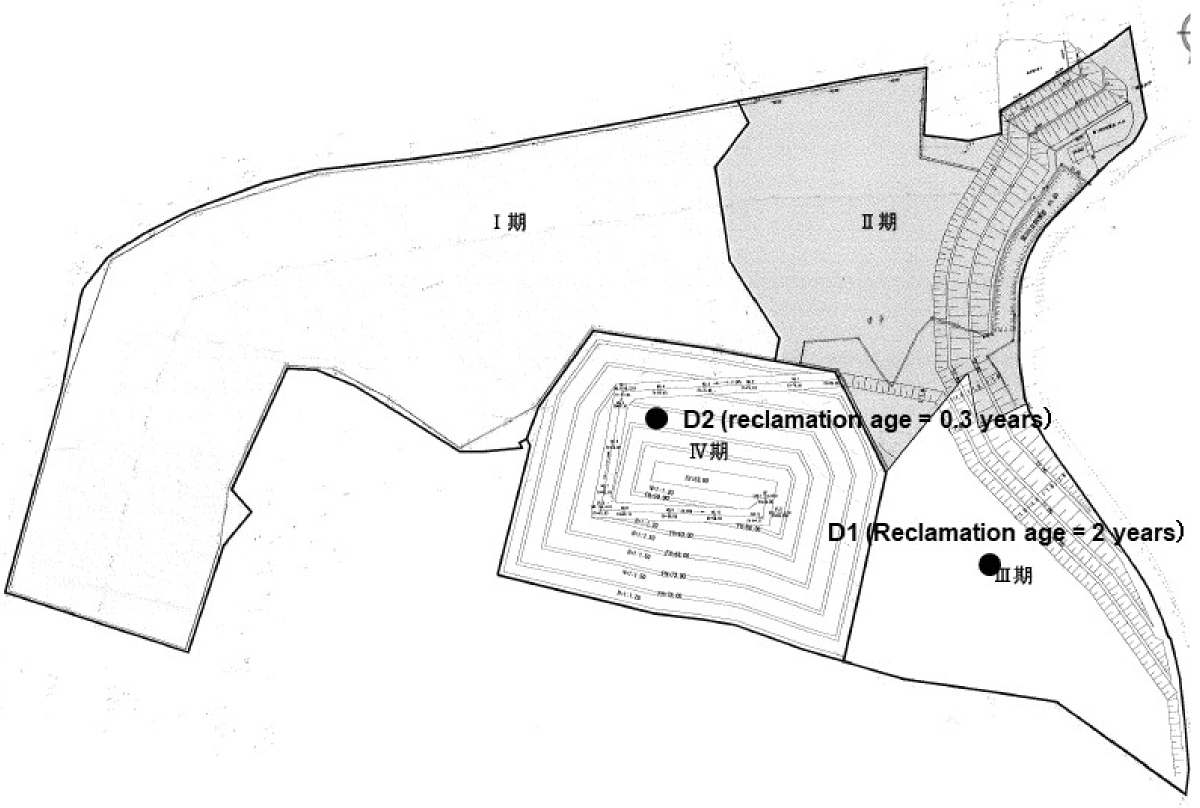


(b) Miyagi landfill B

Figure 3.1 Landfills with different locations



(c) Aichi landfill C



(d) Chiba landfill D

Figure 3.1 Landfills with different locations

Table 3.1 Composition and basic physical properties of the inert waste materials in Japan

Landfills	Location	Composition (%)			Water content (%)	Percentage air voids (%)	Reclamation age (years)	In-situ wet density (g/cm^3)	Dry density (g/cm^3)
		Fibrous > 20 mm	Granular >20 mm	Soil <20 mm					
A (Chiba)	A1	6	30	64	18.8	14.7	0.1	1.35	1.14
	A2	17	13	70	30.0	9.5	19.0	1.46	1.12
	A3	7	44	43	10.0	37.0	0.1	1.50	1.36
	A4	6	18	6	28.0	21.0	15.0	1.60	1.25
B (Miyagi)	B1	31	16	53	35.4	16.8	0.6	1.08	0.80
	B2	27	15	58	18.5	-	10.0	1.19	1.00
	B3	54	45	-	42.0	16.0	3.8	1.40	0.99
C (Aichi)	C1	14	25	57	21.0	41.0	0.0	1.20	0.99
	C2	14	25	57	23.0	29.0	0.9	1.20	0.98
	C3	14	25	57	29.0	22.0	1.8	1.40	1.09
	C4	14	25	57	19.0	14.0	8.0	1.60	1.34
	C5	17	28	43	23.0	17.0	15.0	1.50	1.22
D (Chiba)	D1	4	22	74	16.9	15.7	2.0	1.54	1.32
	D2	3.6	22	74	23.4	16.5	0.3	1.79	1.45

Composition analysis test

Permitted items in landfills were waste plastics, rubber, metal, concrete, glass, & ceramic, debris (including asbestos-containing industrial waste), and industrial waste specified in MOE Notification No. 105. Thorough inspection was conducted at the time of confirmation and disposal. The landfill managements usually conduct employee education including external training and exchanging information with waste discharge sources, collection and transportation companies. For composition analysis, at each location 3-8 points were measured.

For each point, approximately 20–30 kg of inert waste materials was collected and then the total weight of collected materials was measured. After that, the waste was manually sieved by using 20 mm sieve. Zekkos et al. (2010a) indicated that the material ≤ 20 mm was composed of mostly soil-like material. Similar tendency was observed at the sites tested in this study. After sieving, the inert waste materials were divided into three main components as soil like materials (≤ 20 mm), granular materials (> 20 mm), and fibrous waste materials (> 20 mm). Granular materials were again manually subdivided as 'rocks' and 'glasses and potteries.' In fibrous materials, two sub divisions were 'plastics' and 'other fibers.' The different components obtained from composition analysis is shown in Figure 3.2. After dividing, the mass of each part was measured and finally the ratio of each component was calculated. The composition and basic physical properties such as wet density, water content and percentage air voids for all the locations are shown in Table 3.1.

Figure 3.2 Composition Analysis

In-situ density test

In situ wet density, percentage air voids and water content tests were conducted to obtain the basic physical properties of the inert waste materials. The water replacement method was used to determine the in-situ wet density as shown in Figure 3.3. The in-situ density (D) can be obtained as equation $D = M/V$; where, M is the mass of the waste was cut in the site, V is the volume of the waste measured by replacing the soil cut with water.

Figure 3.3 In situ wet density test

Percentage air volume test

For percentage air voids test as shown in Figure 3.4, the cut out waste was placed in a water filled container and water level increment was measured. The percentage air voids (n) can be determined by equation (3.1) as shown below,

$$n = (V - V_{s+w})\,/V \quad\text{.................................}(3.1)$$

Where V is the volume of waste cut out for the in situ density test, V_{s+w} is the volume of the sample as found by the incremental water level (Δh) in the container and Δh is the change in water level after thorough agitation with a stick to let air out of the sample.

CASPOL impact value test

CASPOL impact value test is a quick test to know the strength parameters of the waste. For CASPOL impact value test, CASPOL tool developed by the Kinki Construction Engineering Office, Ministry of Land, Infrastructure, Transportation and Tourism of Japan (1996) was used. In the impact acceleration test, the CASPOL instrument was first properly levelled on the ground and then a rammer with 50 mm diameter and 4.5 kg weight was dropped from a height of 45 cm from the ground surface. The accelerometer attached to the rammer measured the impact value (I_a) which is an indicator of bearing capacity (Yamawaki et al. 2017). Because the rebound of the rammer is affected by stiffness of ground tested, with this test we can estimate the bearing capacity and strength of the ground. Figure 3.5 shows the CASPOL impact value test. The measurement obtained from the CASPOL impact value test are used for a quick estimation of the bearing capacity of the inert waste. Due to the different challenges faced by the researchers during the field tests, this tool is preferred as it is easy to handle and gives quick results. Still, for detailed analysis or accurate results, other test methods should be used instead of CASPOL impact value test.

Figure 3.4 Percentage air voids test

Figure 3.5 CASPOL impact value test

Angle of repose test

Strength parameters related to the slope stability of the waste layers were obtained through angle of repose test which is a quick test. Angle of repose is the steepest slope angle at which a heap of granular material can remain stable under gravity by virtue of own physical and chemical properties (Khanal et al. 2017). To measure the angle of repose, inert waste was first excavated from the landfill using a 0.7 m^3 backhoe, and then dropped from approximately 2.0 m height to make a heap. The slope angle before the collapse is called as critical angle of repose (α_c) and the slope angle after the avalanche is known as the angle of repose after avalanche (α_a) (Matsukura et al. 1989). To calculate the slope stability, the angle of repose after avalanche was taken as the angle of repose, because Yamawaki et al. (2017) found that in case of flat grounds, angle of repose after avalanche is the maximum slope gradient at which the slope failure or crack does not occur. Figure 3.6 shows the measurement of angle of repose on sites.

(a) Preparation of heap (b) Measuring the slope angle

Figure 3.6 Angle of repose measurement

In-situ direct shear test

The shear strength parameters, cohesion 'c' and internal angle of friction 'φ', can be measured with direct shear test. For this research, a large sized direct shear test apparatus developed by Omine et al. (2014) was used as shown in Figure 3.7. The size of the shear box for direct shear test was 30 cm × 30 cm × 15 cm. To minimize the size effect, visual inspection was carried out in the solid waste deposit area where specimen was supposed to be prepared, so that the area did not include large sized inert waste components. The size of flexible, fibrous waste materials was allowed to be larger than the granular component because they could fold during specimen preparation (Zekkos et al. 2010a). After selecting the solid waste deposit area, a specimen with dimensions of 30 cm × 30 cm × 15 cm was trimmed out from the area in such a way that the bottom part of the specimen was still connected to the waste landfill and undisturbed. Fibrous materials on the sides of the block specimen were cut by a grinder to get a proper shape and the shear box of the in situ direct shear test apparatus was fitted around the specimen. The shear box could fit to the specimen. After fixing the direct shear test apparatus, the specimens were sheared with a shearing rate of 1.0 mm/min under three normal stresses of 3.70, 14.10, 25.55 kN/m^2. The normal stress values were smaller because there was a limitation of weight and reaction force. In case of no clear peak strength, the strength at a horizontal displacement of 35 mm was used to calculate the shear parameters.

(a) Preparation of the sample (b) Measuring shear strength

Figure 3.7 Direct shear test

3.2.2 Results and discussions

Composition analysis test

From composition analysis, the composition of the waste materials was confirmed. The inert waste materials were consisting of rocks, glasses, potteries, soil like materials, plastics, other fibers with very little amount of woods and metals. Three main components were found as: 3.6 to 54% of fibrous content (consisting of ‘plastics’ and ‘other fibers’ > 20 mm), 13 to 45% of granular content (consisting of ‘rocks’ and ‘glasses and potteries’ > 20 mm), and 43 to 74% of soil-like content (≤ 20 mm). The inert waste materials contained significant amount of soil fractions with an average value of 59% which is the maximum among all the three components. There is one exception at B3 location, where no soil component was found and fibrous content was highest. The average granular content was found as 25%. The average fibrous content was found as the lowest among all three components with a value of 16%. Composition of inert waste landfills at the 14 locations of 4 landfills is shown in Figure 3.8.

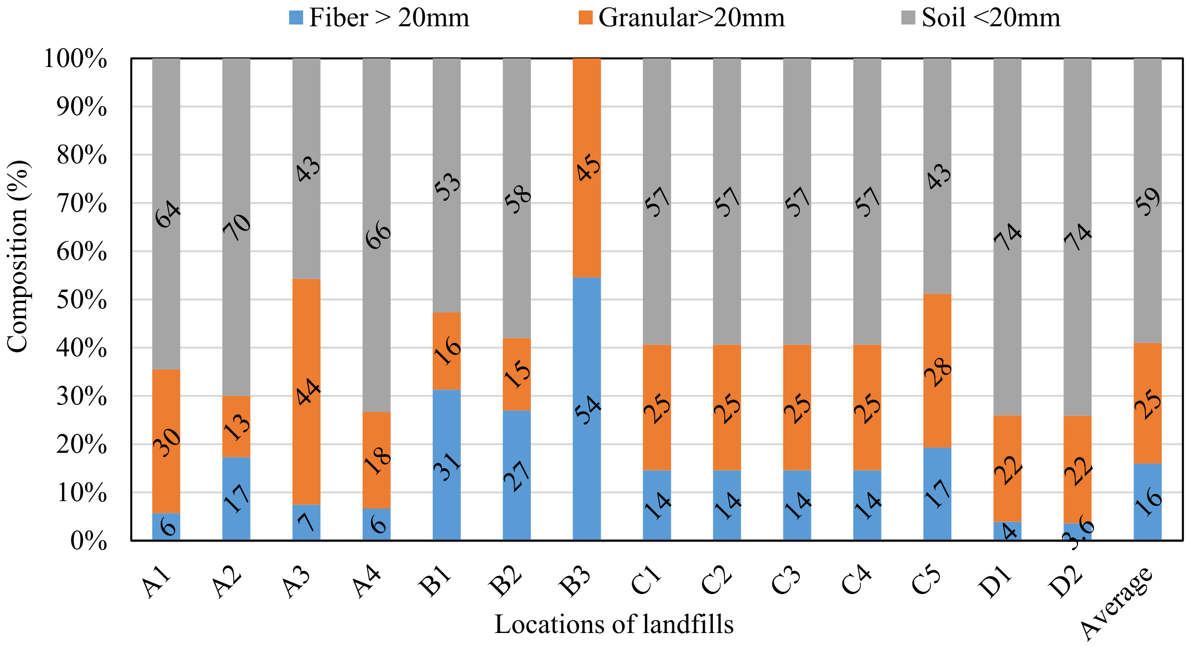


Figure 3.8 Composition of inert waste landfills at the 14 locations of 4 landfills

In-situ density test

The dry density decreased with decrease in soil-like content and increase in fibrous content around 30%. The decrease in dry density with increase in fibrous content may be due to two reasons. Firstly, for the same volume, specific gravity of fibrous content was lower than the granular or soil-like content and this low specific gravity made the waste dry density lower. Secondly, the bouncy nature of fibrous content made the compaction of the waste less effective thus decreased the dry density. Increase in soil-like content showed significant increase in dry density up to 1.8 times more than the lowest value of dry density found among the 14 locations. The voids were filled with soil, increasing the dry density. Figure 3.9 shows the change in dry density with age after reclamation for (a) fibrous and (b) soil-like content.

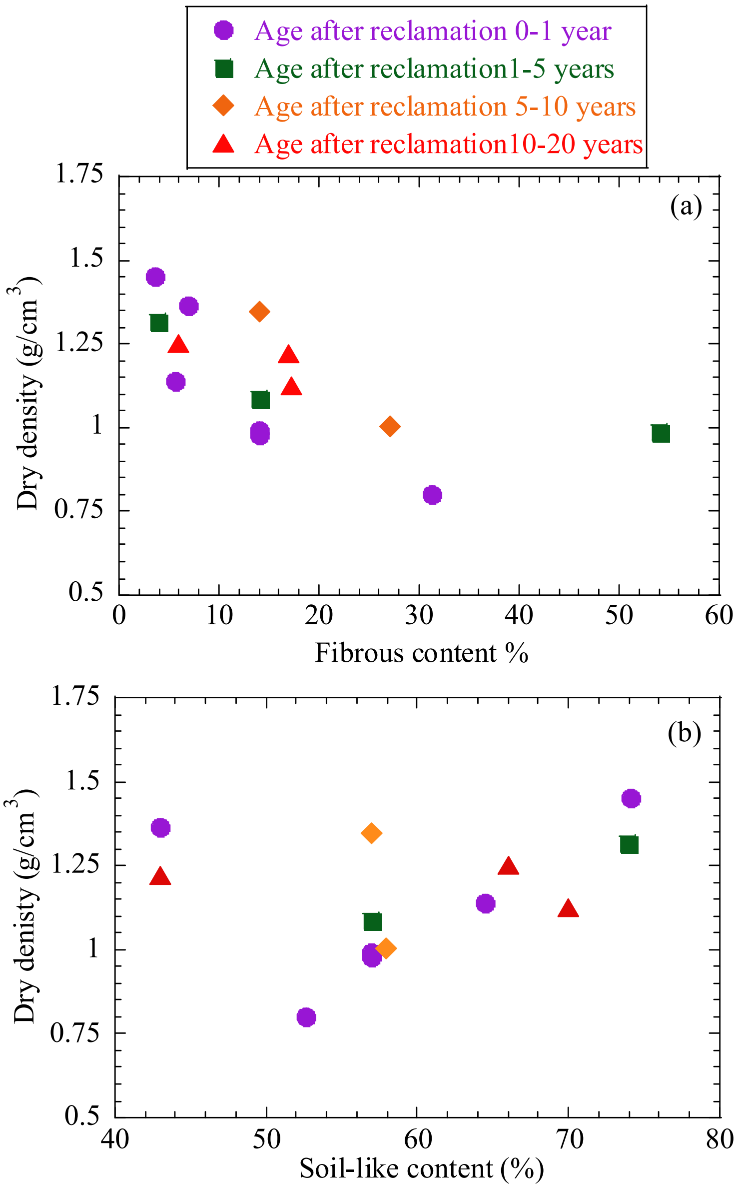


Figure 3.9 Change in dry density with age after reclamation for (a) fibrous and (b) soil-like content

Percentage air volume test and water content

Figure 3.10 shows change in water content and percentage air voids for (a) fibrous content, (b) granular content and (c) age after reclamation. The water content increased and percentage air voids decreased with increase in fibrous content and age after reclamation. With time, large sized fibrous fractions stored rain water and organic leachate, thus increasing the water content. With increase in water content, the voids in the waste ground were filled with more water than air, which decreased the percentage air voids. The water content decreased and percentage air voids increased with increase in granular content. Granular fractions could not store water like the large fibrous fractions, so, there is a decrease the water content.

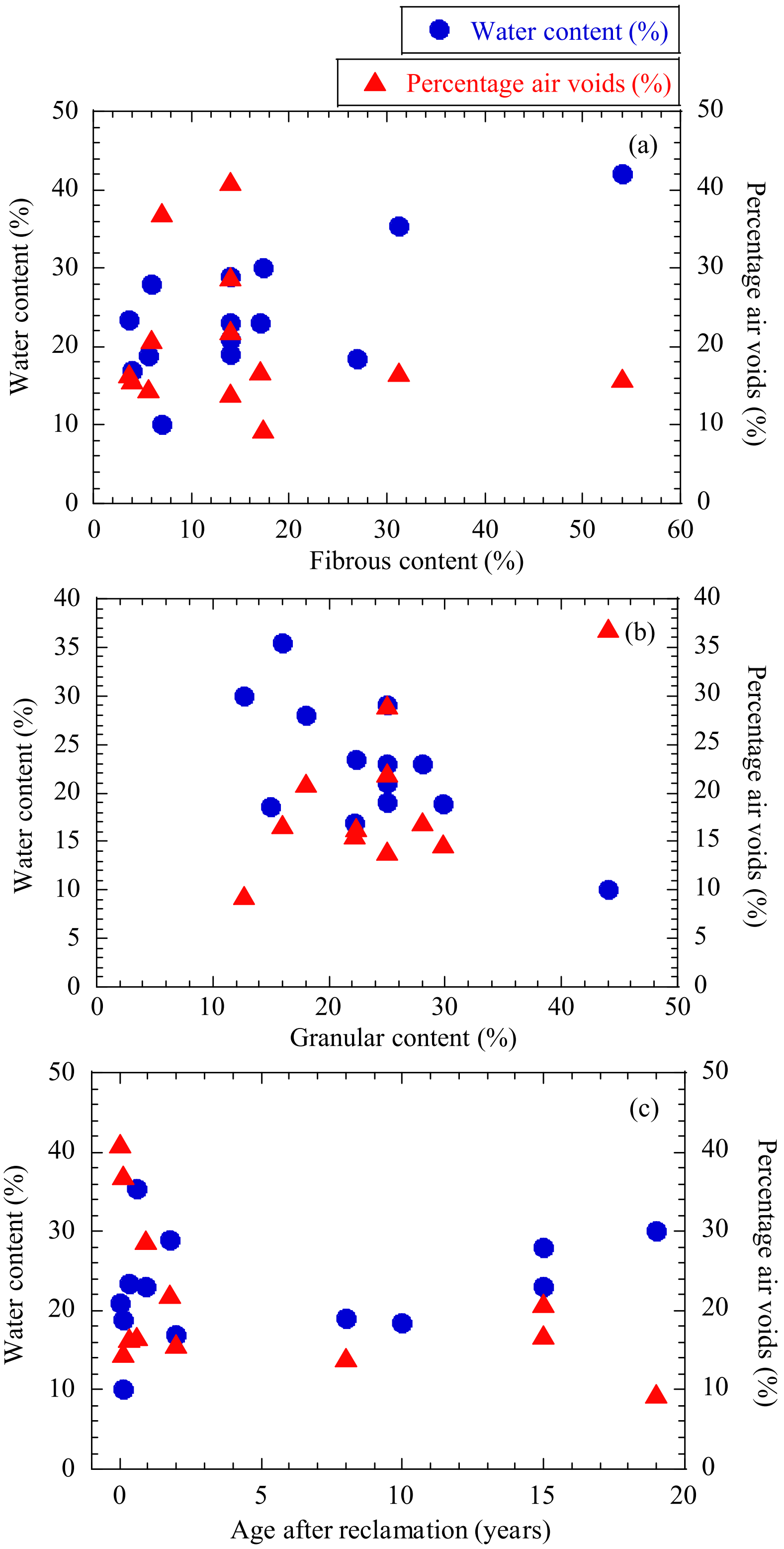


Figure 3.10 Change in water content and percentage air voids for (a) fibrous content, (b) granular content and (c) age after reclamation

CASPOL impact value test

Figure 3.11 shows change in impact value with increase in dry density, fibrous content, soil-like content and age of the inert waste landfill locations. Impact value increased with increase in dry density and soil-like content. Impact value is an indicator of the bearing capacity of soil and also for the waste material. Higher the dry density, voids were lesser and bearing capacity became more. Impact value decreased with increase in fibrous content under 17% and age after reclamation. Though regular visual inspections were carried out to prevent inclusion of biodegradable wastes (e.g., organic materials), still sometimes such matters are found in inert waste landfills (Morotomi et al. 2018). Decomposition of biodegradable waste and water penetration through the landfill with age after reclamation were considered to be the reason for lower impact value of older landfills. For the condition of soil-like > granular> fibrous content, the dry density was maximum thus the impact value was higher. Under very high fibrous condition, if granular content >> soil-like content, then impact value was higher.

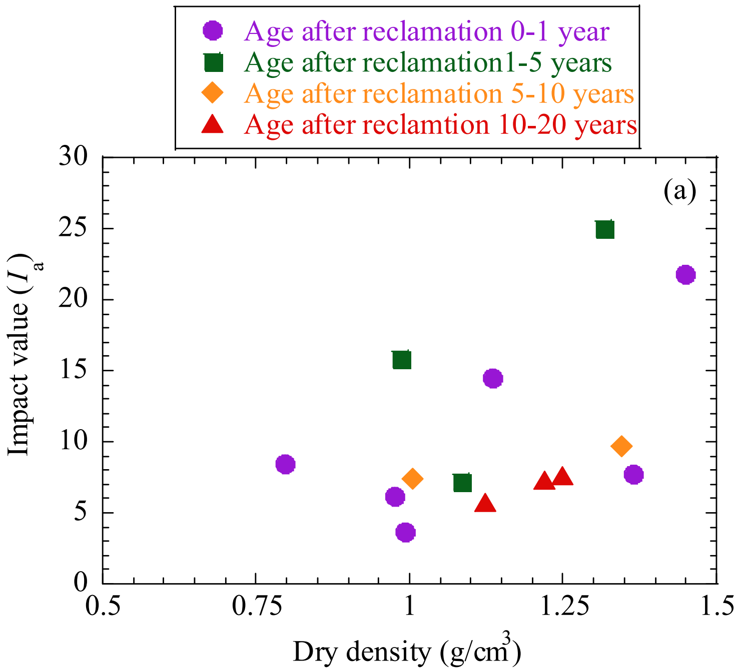


Figure 3.11 Change in impact value with age after reclamation for (a) dry density

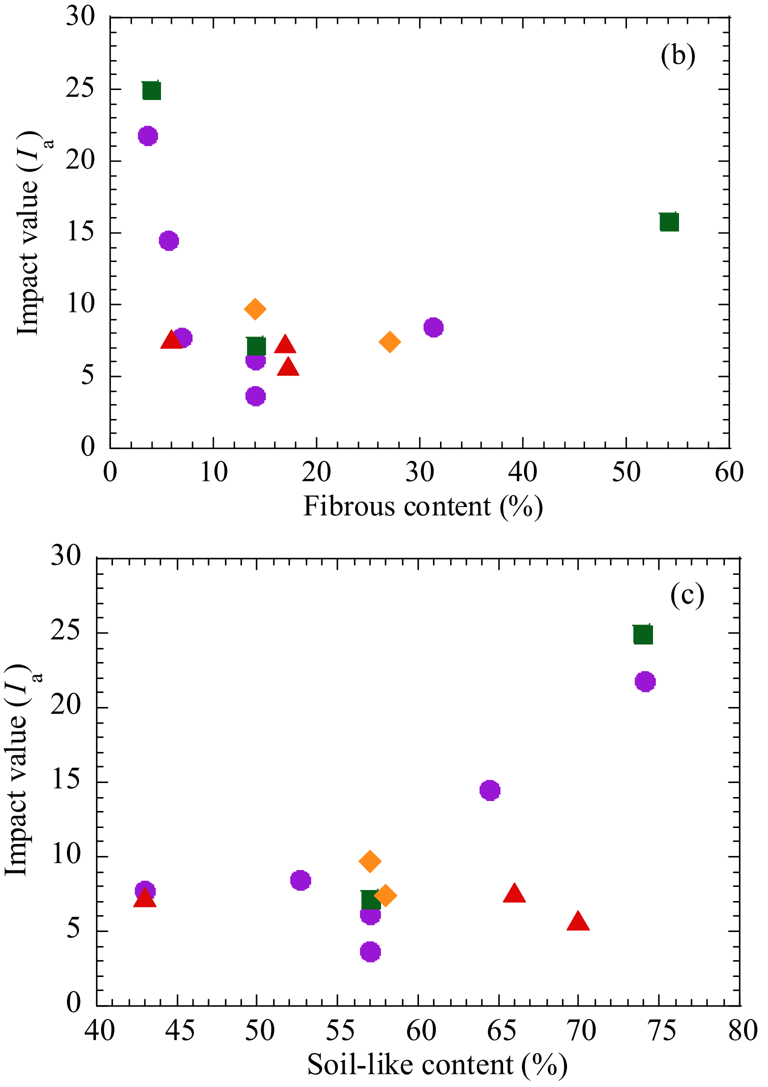


Figure 3.11 Change in impact value with age after reclamation for (b) fibrous and (c) soil-like content

Angle of repose test

Figure 3.12 shows the change in critical angle of repose (α_c), angle of repose after avalanche (α_a), and (α_c- α_a) with (a) fibrous content and (b) soil-like content. For all the locations, angle of repose after avalanche (α_a) was within the range of 34–44°. The variation in critical angle of repose (α_c), angle of repose after avalanche (α_a), and the difference between the two ($\alpha_c - \alpha_a$) with increase in fibrous content were studied. With increase in fibrous content, ($\alpha_c - \alpha_a$) slightly increased and with increase in soil-like content it slightly decreased. The fibrous fractions provided frictional surface thus increased the inter-particle contact friction and tensile resistance, which bonded the materials together to make higher value of critical angle of repose. In case of inert waste having higher fibrous content and lower soil-like content, due to the low specific gravity and bulkiness of the fibers, the density of the heap was less and the voids were more making the heap looser than the case of high soil-like content. Because of this looseness, in case of high fibrous content, the heap became wider and shorter after avalanche, thus increasing the ($\alpha_c - \alpha_a$) value. In case of higher soil-like content, the heap is denser, so there was not much decrease in angle of repose after avalanche, which made the ($\alpha_c - \alpha_a$) value lower. Explanatory diagrams for these behaviors are shown in Figure 3.13.

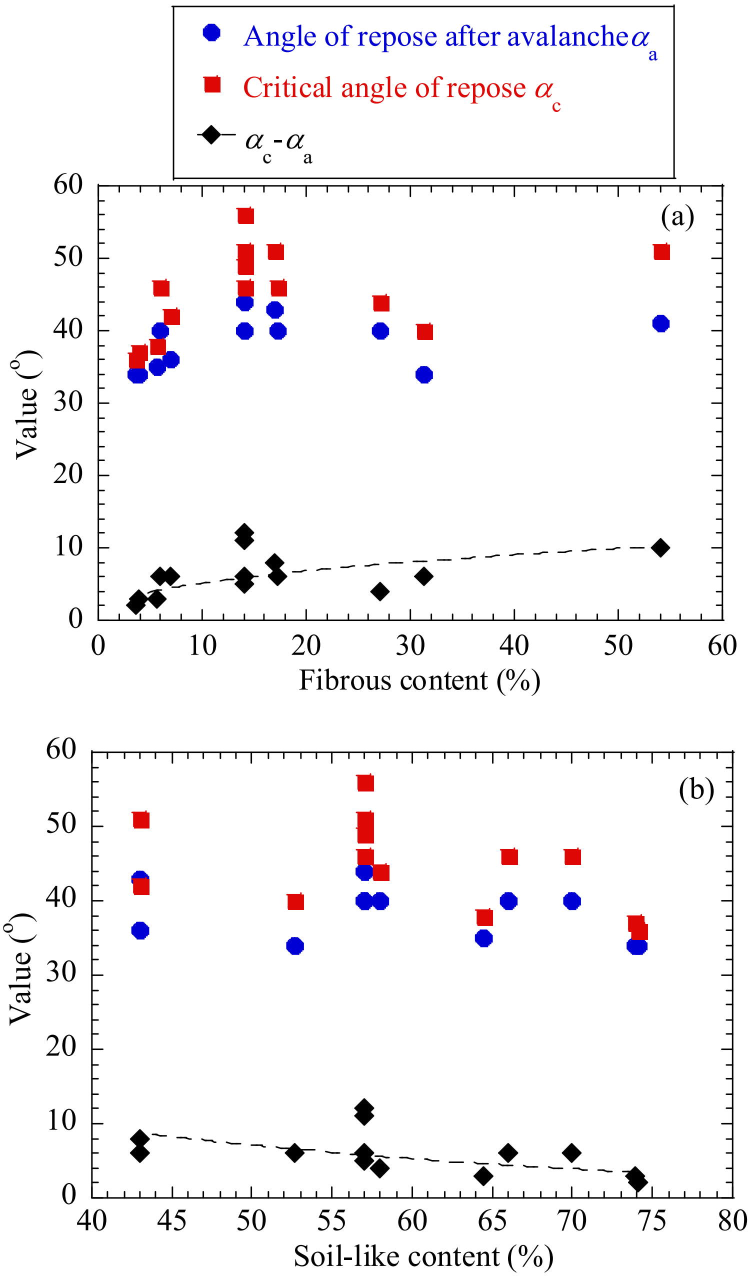


Figure 3.12 Change in critical angle of repose (α_c), angle of repose after avalanche (α_a), and (α_c- α_a) with (a) fibrous content and (b) soil-like content

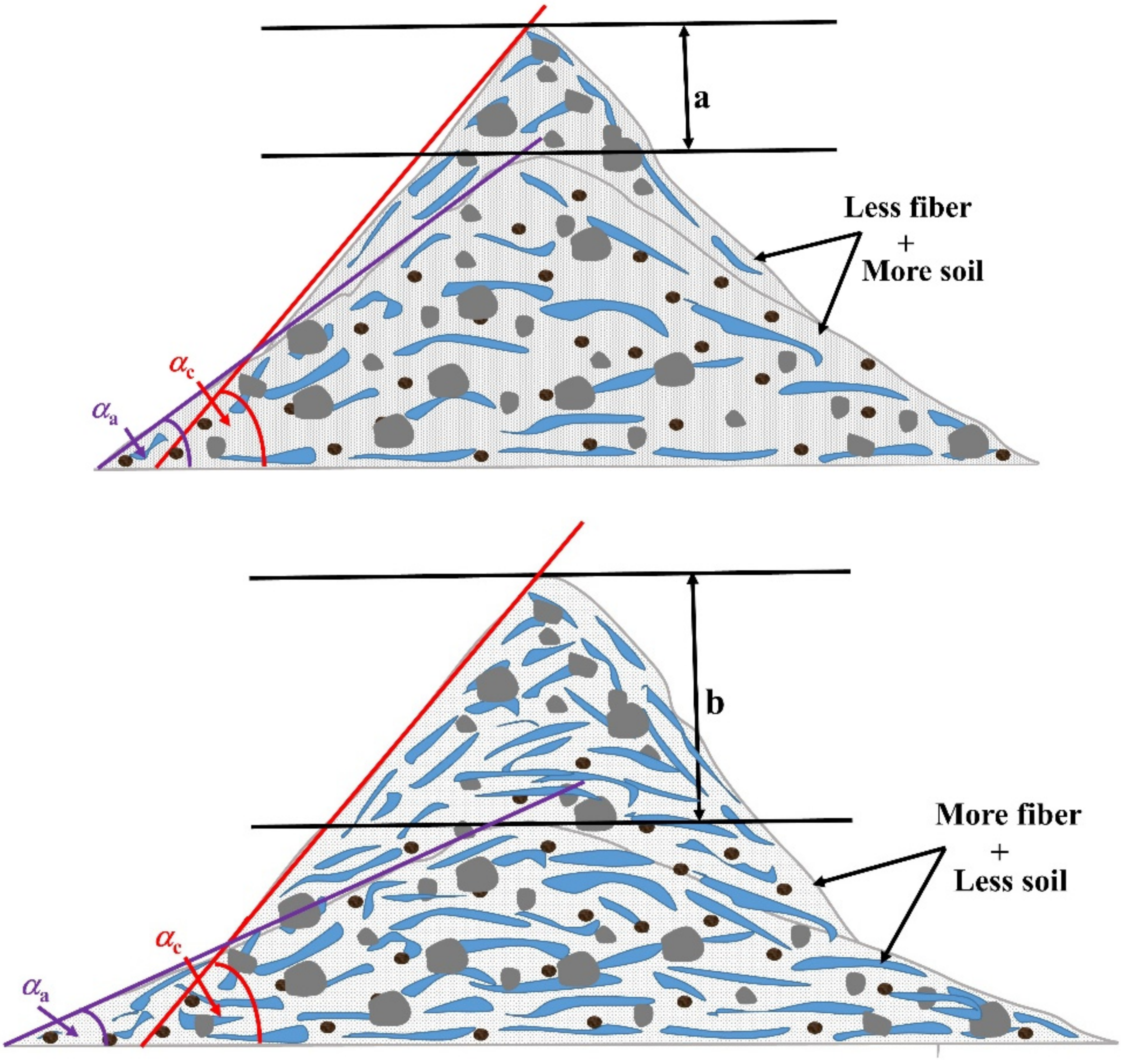


Figure 3.13 Explanatory diagrams for change in α_c- α_a with increase in fibrous content and soil-like content

In-situ direct shear test

For direct shear test, to maintain the accuracy in results, out of 13 tests, 6 numbers of tests where the graphs of shear stress vs normal stress, with a R^2 value more than 0.85 were considered for strength measurement. Figure 3.14 shows shear stress vs horizontal displacement relationship of three locations C3, A2, and B2 with fibrous content 14%, 17% and 27% under normal stresses of 3.70, 14.10, 25.55 kN/m^2 respectively. From the graphs, a varied range of shear stress vs. horizontal displacement was observed. However, in case of landfill site with

F.C. 27%, the peak value was not clear. Higher amount of fibrous content made unclear peak value. In this case, the stress at a horizontal displacement of 35 mm was used to determine the shear strength. After getting the maximum shear stresses for each normal stress, the strength parameters *c* and *φ* (cohesion and internal angle of friction) were calculated for each site. The composition and strength parameters obtained from direct shear test of each location is given in Table 3.2

Table 3.2 Composition and shear strength parameters for direct shear test

Location	Fibrous > 20 mm	Granular >20 mm	Soil <20 mm	cohesion (*c*)	internal angle of friction (*φ*)
A2	17	13	70	20.92	21.68
B1	31	16	53	10	51
B2	27	15	58	11	51
C2	14	25	57	2	59
C3	14	25	57	8	36
C4	14	25	57	18	36

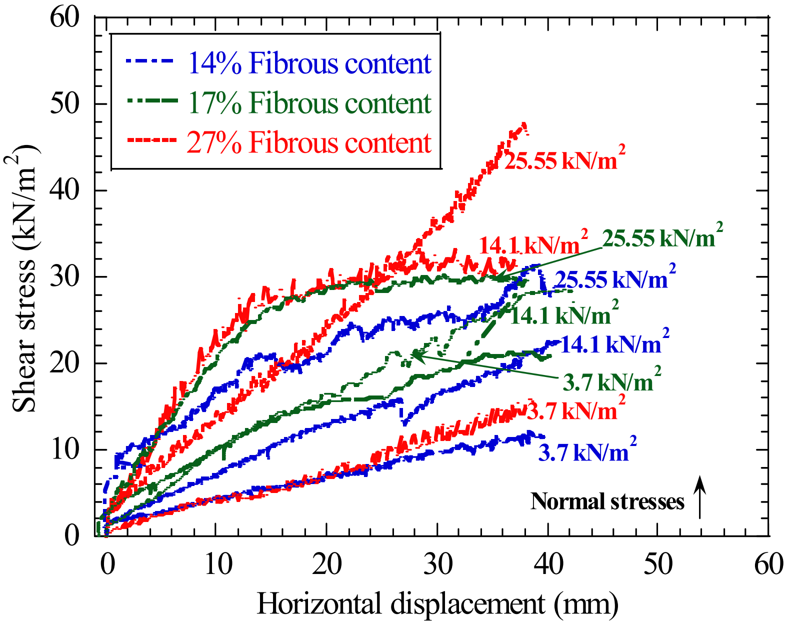


Figure 3.14 Shear stress vs horizontal displacement

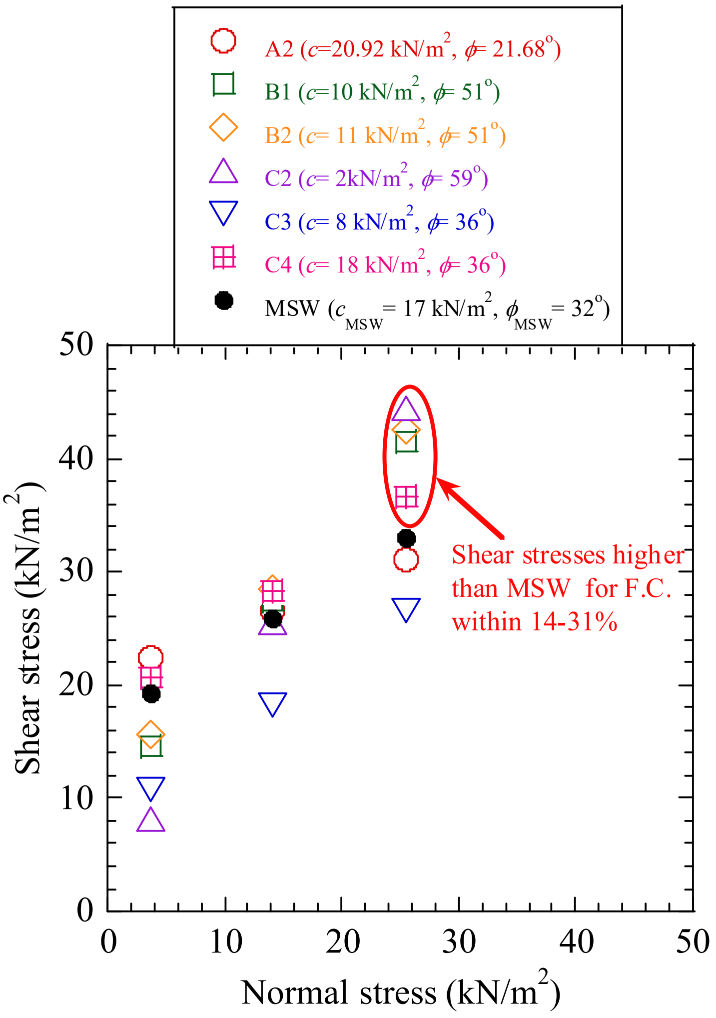


Figure 3.15 Shear stress with respect to normal stress

Figure 3.15 shows the shear stress with respect to normal stress. For shear stress with respect to normal stress graph, cohesion (*c)* values were found within the range of 2–21 kN/m^2 and internal angle of friction (*φ)* was found within the range of 22–59º. These strength values of inert wastes were then compared with the average effective shear stress parameters of municipal solid wastes ($c_{MSW} = 17$ kN/m^2 and $\varphi_{MSW} = 32$º) obtained from 288 data points from 18 countries (Ramaiah et al. 2017). Under the normal stress of 25.55 kN/m^2, the inert waste strength parameters gave higher shear strengths than the municipal solid wastes, particularly for landfills having fibrous fractions ranging from 14 to 31%.

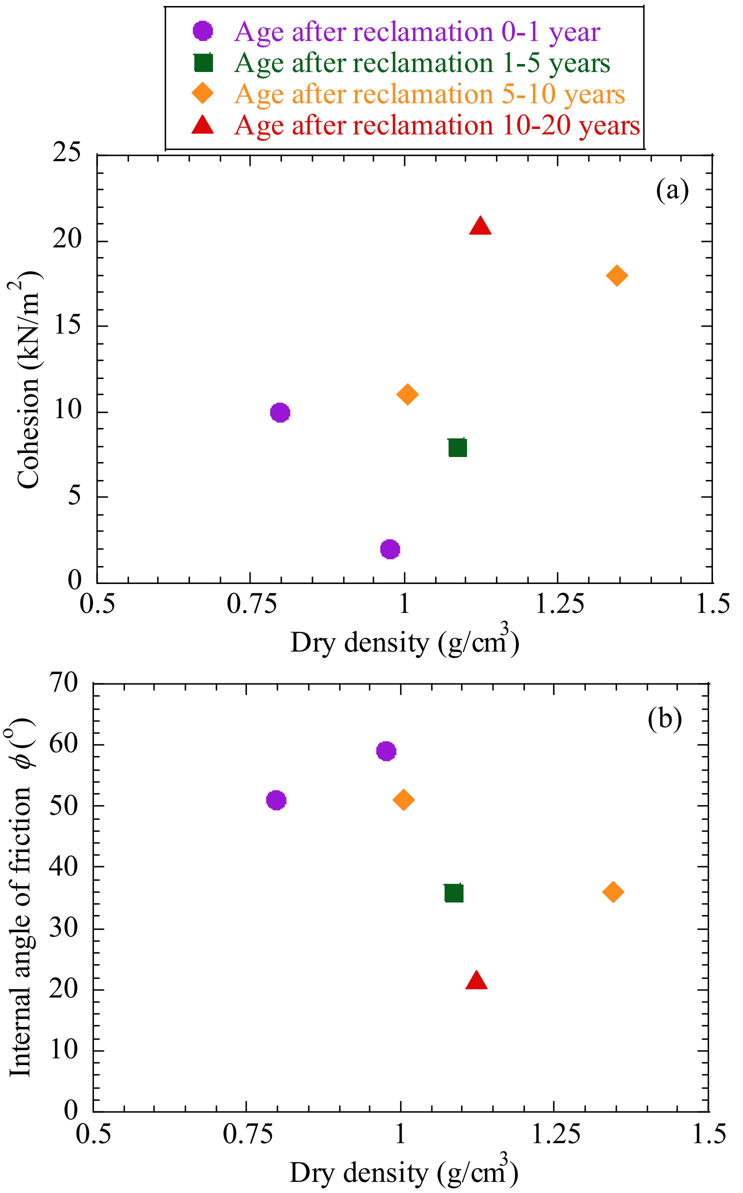


Figure 3.16 Change in strength parameters with increase in dry density; (a) *c* and (b) ϕ

Figure 3.16 shows the change in strength parameters with increase in dry density. Cohesion increased and internal angle of friction decreased with age after reclamation. It can be ascribed to the decomposition of waste. Reddy et al. (2011) also found similar behavior for MSW due to decomposition. With increase in dry density, cohesion (*c)* increased and internal angle of friction (*φ)* decreased. This behavior can be attributed to heavy compaction. Figure 3.16 shows the behavior of compacted soil and change of cohesion and angle of friction due to heavy compaction.

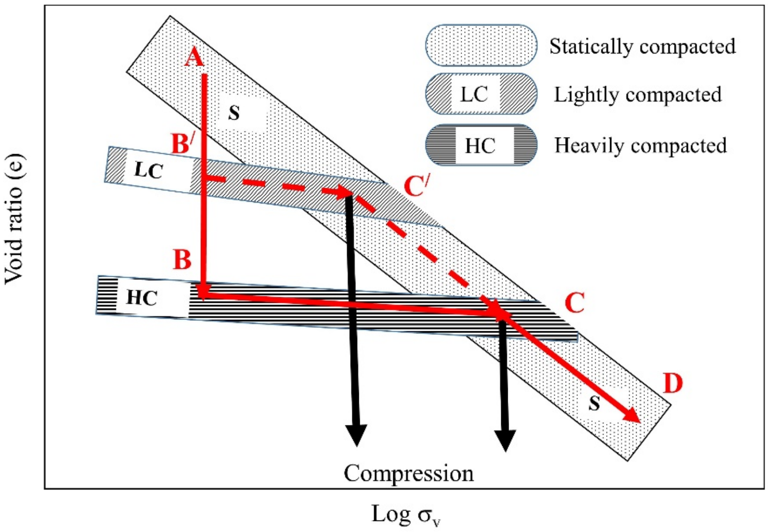


Figure 3.17 Behavior of compacted soil under compression (Modified figure taken originally from Ohta et al. 1991)

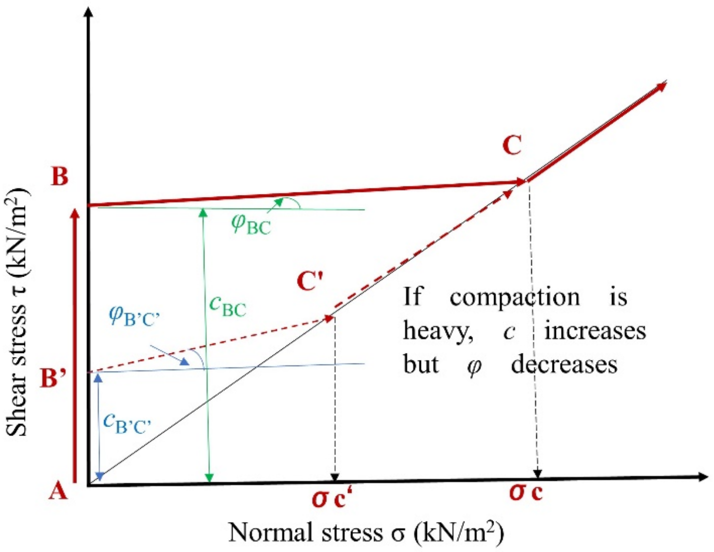


Figure 3.18 Change in cohesion (*c*) and internal angle of friction (*φ*) due to heavy compaction

In Figure 3.17, the compressibility of statically compacted, lightly compacted, and heavily compacted soils is explained. According to Ohta et al. (1991), the slope is first A→D for statically compacted materials. If heavy compaction is applied than A point moves downward and finally after finishing the compaction, when the unloading is done, then the shape becomes B→C. In this case, the B point is at higher position than C due to the material's tendency to return to the previous shape after unloading of heavy loads. Similarly, for lighter compaction, the shape becomes B′→C′. If we plot all these conditions as normal stress vs shear stress conditions, we can understand the change in *c* and *φ* values with increase in compaction degree. In Figure 3.18 the cohesion is increasing ($c_{BC} > c_{B'C'}$) and internal angle of friction decreasing

($\varphi_{BC} < \varphi_{B'C'}$) for heavy compaction (BC) condition as compared to light compaction (B'C'). Therefore, the reason of change in *c* and *φ* with increase of dry density was not material dependent, it merely depended on overburden pressure. In this case, strength parameters may be considered as apparent, not as essential material constant. As heavy landfill compactors were used in the sites of the inert waste landfills in Japan, therefore, it was assumed that the waste materials were heavily compacted. However, compaction of landfills with more fibrous content were not easy because, due to the bulkiness and bouncy nature, the fibrous content tends to rebound to its original shape thus decreasing the density, thus making lower *c* and higher *φ* values.

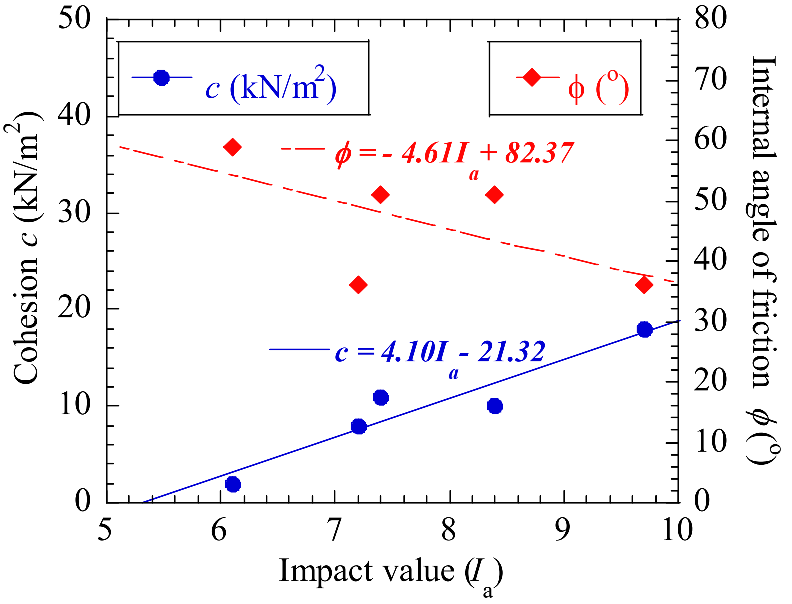


Figure 3.19 Correlation of impact value (I_a) with cohesion (*c*) and internal angle of friction (*φ*) for IWLs within age of reclamation of 10 years

In Figure 3.19, the correlation between CASPOL impact value and the shear strength parameters cohesion and internal angle of friction for inert waste landfills of age within 10 years is shown. The correlation calculated for *c, φ* and I_a for inert waste landfill are given below:

$$c = 4.10 I_a - 21.32 \quad \text{(3.2)}$$

$$\varphi = -4.61 I_a + 82.37 \quad \text{(3.3)}$$

where, c = cohesion (kN/m^2), φ = internal angle of friction and I_a = impact value

With increase in I_a, c increased and φ decreased. These two correlations may be useful for landfilling stage of an inert waste landfill, where a quick idea about the shear strength parameters cohesion and internal angle of friction of inert waste materials can be obtained by just getting the CASPOL impact value and the slope stability of the landfill can be evaluated. Using CASPOL impact value test would make it quicker and easier, compared to other time-consuming shear tests such as direct shear test etc.

3.2.3 Estimation of S.G. values for fibrous, granular and soil-like fractions (G_f, G_g and G_s)

From the physical properties obtained in the inert waste landfills, the specific gravities of the inert waste were calculated. These calculated specific gravities were for the entire inert waste containing all the three main components, not for individual components. To know the material properties of the components and their exact packing condition in the inert waste, it is necessary to know the individual specific gravities of each component. If the exact packing condition of the inert waste materials is known, then the variation in results occurred due to heterogeneity of the waste can be examined and more detailed strength analysis is possible. Usually, to determine the specific gravity of each component, laboratory experiments can be conducted, but in this study, a new and quick approach was followed to estimate the approximate values for individual specific gravities (S.G.) for fibrous, granular and soil fractions i.e. G_f, G_g, and G_s for the 14 locations of inert waste landfills. In this method, the specific gravity of each component can be quickly estimated by using some formulas and following the steps discussed below.

First, field S.G. for all locations were calculated using the formula in equation (3.4).

$$\gamma_d = \frac{(1-n_a)G_F\gamma_w}{1+wG_F} \tag{3.4}$$

Where, γ_d = Dry unit weight, n_a = Percentage air voids, G_F = Field S.G., γ_w = Unit weight of water and w = Water content.

Next, calculated S.G. was obtained for all locations from the formula in equation (3.5)

$$G_{c} = \frac{P_{f} + P_{g} + P_{s}}{\frac{P_{f}}{G_{f}} + \frac{P_{g}}{G_{g}} + \frac{P_{s}}{G_{s}}} \tag{3.5}$$

Where P_f, P_g, and P_s = percentage of fibrous, granular, and soil fractions, G_f, G_g, and G_s = assumed S.G. of fibrous, granular, and soil fractions and G_C = Calculated S.G. using assumed S.G of each fraction. As G_f, G_g, and G_s are assumed, to estimate the real S.G. values of each fraction, first, the limits of G_f, G_g, and G_s are taken as $G_f^* = 0.90–1.27$, $G_g^* = 2.30–2.60$, and $G_s^* = 2.40–2.90$ respectively. These limits were chosen from different literatures (Lide 2008, Brandrup and Immergut 1989, Alger 1989 and Wong 2009). Within the selected limits, G_C for all locations were calculated for many combinations of G_f, G_g and G_s and were compared with G_F values so that $\Sigma(G_F - G_C)^2$ was minimum. Finally, only for one combination of G_f, G_g, and G_s the $\Sigma(G_F - G_C)^2$ was found minimum. The specific gravities from that combination were considered as the final estimated specific gravities for fibrous, granular and soil fractions. In the first combination process to calculate G_C, the G_f and G_g values were taken with a difference of 0.05 within their limits and values of G_s were taken with a difference of 0.1 within its limit. From the first combination, the new limit values giving minimum error were obtained as ($G_f^{**} = 0.95–1.00$, $G_g^{**} = 2.55–2.60$, and $G_s^{**} = 2.75–2.85$). In the second combination process, the values for G_f and G_s were taken with a difference of 0.05 within their limits and values for G_g were taken with a difference of 0.01 within its limit. From the second step, the limit values for each fraction giving minimum error were obtained as ($G_f^{***} = 1.00–1.05$, $G_g^{***} = 2.58–2.60$, and $G_s^{***} = 2.75–2.80$). In the third combination process, the values for G_f, G_g and G_s were taken with a difference of 0.01 within their limits. In this third combination process, there was only one combination for which $\Sigma(G_F - G_C)^2$ was minimum. From this combination, the final specific gravity values for fibrous, granular and soil fractions in the inert waste landfills were estimated as 1.0, 2.60, and 2.80 respectively.

The estimated specific gravity values of the three main components are useful because from these values the types of materials present in the inert waste can be predicted. For example, the estimated specific gravity of fibrous fractions containing both plastics and other fibers was closer to the specific gravity value of plastics which is usually ranged between 0.92–0.95 (Wong 2009). Therefore, it may be predicted that the fibrous fractions of inert waste in the 14 locations were mostly consists of plastics than other fibers. The specific gravity estimated for soil fractions was higher than regular soils which indicated the possibility of presence of minerals such as iron etc. As we already know the masses of each fractions in the inert waste, we can also calculate the volume of individual components in inert waste which may give us the idea about the actual packing condition of the inert waste. The exact packing condition of the inert waste materials assists to understand the variation in results occurred due to heterogeneity of the waste to achieve detailed strength analysis. Comparison of field and calculated S.G. values is shown in Figure 3.20.

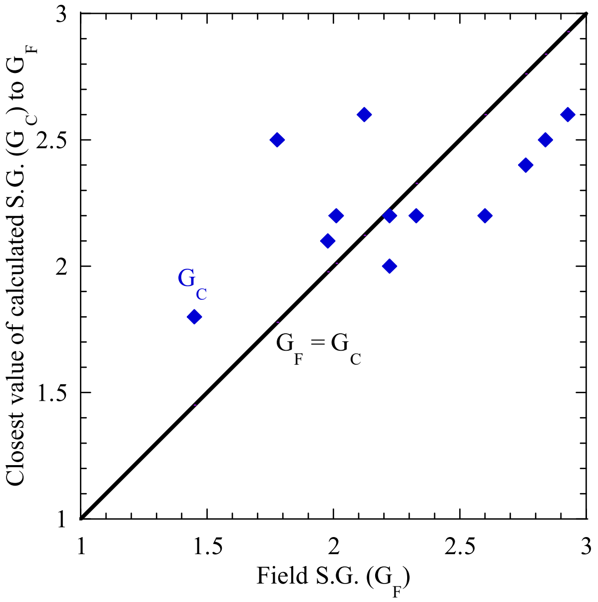


Figure 3.20 Comparison of field and calculated S.G. values

3.3 Laboratory direct shear test

Laboratory direct shear test was conducted with the inert waste material to compare the results obtained from in-situ tests and to have a better understanding of the effect of fibrous fractions on inert waste. The waste materials were collected from inert waste landfill sites. Fibrous fractions were first separated and then 3-16% fibrous fractions were mixed with the inert waste.

3.3.1 Methods and materials

Specimens were prepared with adjusted composition using inert waste collected from the sites A, B (Kanto sample) and C, D (Tohoku sample). Three types of materials were sieved out with a sieve of 20 mm size: fibrous material, fraction finer than 20 mm and granular material. Fibrous material consists of plastics and other fibers; granular material consists of gravel, glass and pottery. Table 3.3 shows the conditions of each cases. The average value of the composition analyses conducted at the sites was taken as the design composition of the waste. The fibrous fractions were first separated and then mixed with the inert waste with rate of 3%, 6%, 11%, and 16% for both samples. The design water contents and dry densities of Kanto samples were taken as about same values as of site A, and of Tohoku samples were taken as same values of site C. Figure 3.21 shows particle size distribution of fibrous materials and granular materials of each samples. Shear property of the waste was evaluated using direct shear apparatus developed by Miyamoto et al. (2015). The size of shear box is 30 cm in width, 30 cm in length and 15 cm in height. Specimens were prepared by filling the samples into the shear box in three layers and compacting each layer 25 times with a rammer of 1.6 kg weight which was dropped from 30 cm height. The specimens were then consolidated under designed compression pressures of 3.7, 14.1, 24.6 kN/m^2 till the settlement became constant or in 10 mm in the case of settlement did not become constant. After consolidation, direct shear test was conducted with a shear velocity of 0.88 mm/min till the shear stress reaches the peak. In the case of shear stress did not show any peak, shearing stress at a shear displacement of 35 mm was considered as shear strength. Normal stresses for the test were 3.7, 14.1, 24.6 kN/m^2. Specimens were prepared by iterative method, and the number of samples was one in all cases.

Table 3.3 Experimental conditions of laboratory direct shear tests

Sample	Composition (%)			Water Content (%)	Dry Density (g/cm^3)
	Fibrous Material	Fraction finer than 20 mm	Granular Material		
Kanto sample	3	80	17	24.0	1.14
	6	77		21.4	1.11
	11	72		24.0	1.05
	16	67		24.0	1.05
Tohoku sample	3	80		42.7	0.83
	6	77		39.8	0.83
	11	72		38.5	0.83
	16	67		38.5	0.81

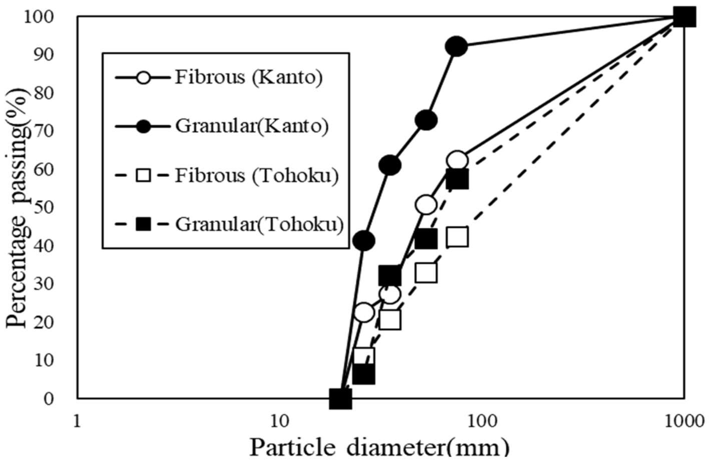


Figure 3.21 Particle size distribution of fibrous material and granular material of each sample

3.3.2 Results and discussion

Figure 3.22 shows the relationship between the fibrous content and shear strength of the inert waste. Under normal stress of 3.7 kN/m^2, shear strength of all samples was almost constant, and it did not show much variation with increase in the proportion of fibrous materials. On the other hand, shear strength decreased with an increase of fibrous materials to a certain limit, in the case of normal stresses of 14.1 and 24.6 kN/m^2.

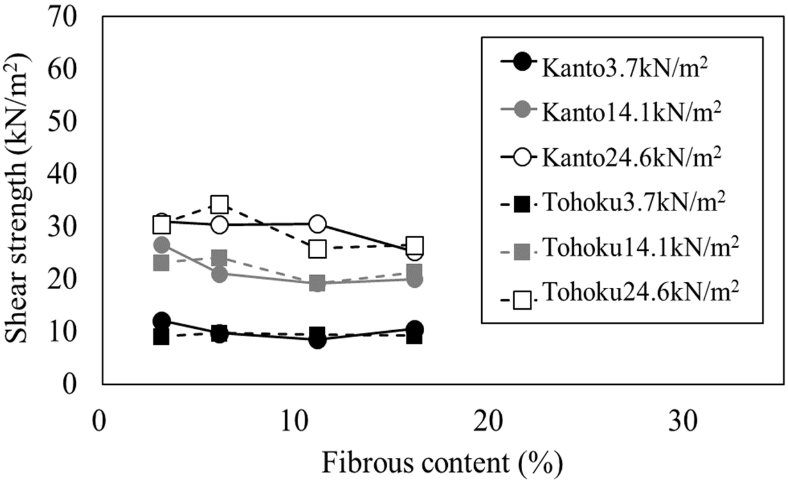
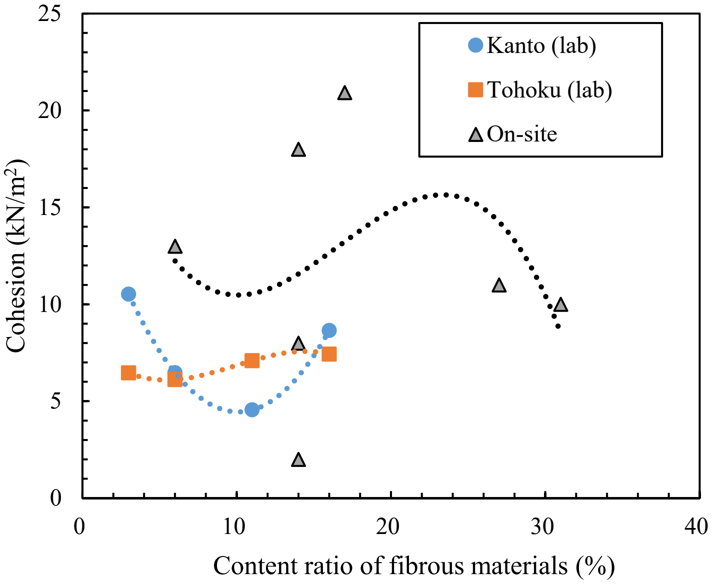
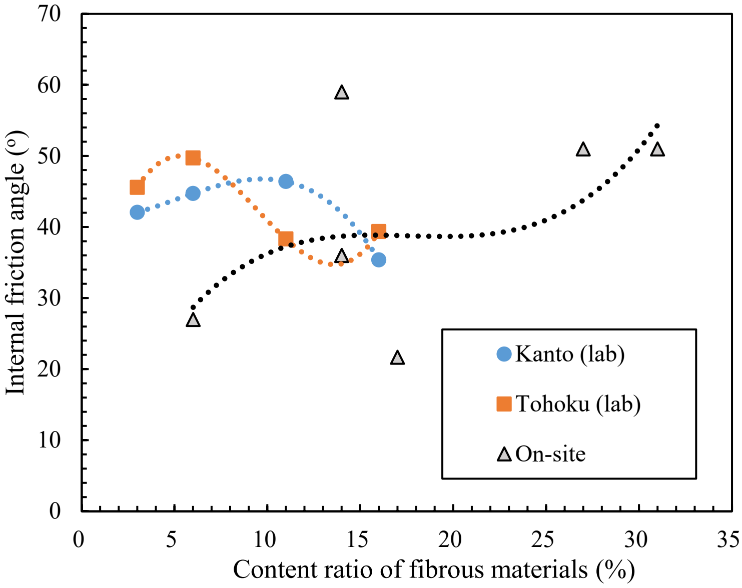


Figure 3.22 Relationship between the content ratio of fibrous materials and shear strength of the waste

Figure 3.23 shows the relationship of fibrous content and strength parameters (cohesion and internal friction angle) for laboratory tests and on-site test. For laboratory test, the cohesion first decreased and then increased, and the internal friction angle first increased and then decreased with an increase in the proportion of fibrous materials to a certain extent. This result is similar to the onsite behavior of strength parameters under specific limit of fibrous materials. The behavior of the changes of strength parameters depended on the samples. Therefore, this behavior was assumed as a result of difference of the basic properties (size, shape, porosity, etc.) of the waste. This change of strength property with an increase in a proportion of fibrous materials was also observed by Miyamoto et al. (2015).



(a) Change in cohesion with increase in fibrous fractions



(b) Change in internal friction angle with increase in fibrous fractions

Figure 3.23 Relationships between fibrous materials and strength parameters

3.4 Laboratory triaxial test

laboratory compaction tests and triaxial tests were also carried out on the inert waste materials (<19 mm without fiber) collected form a Japanese inert waste landfill site, mixed with artificially made fibrous contents at different ratio of weights to understand the change in mechanical properties of inert waste due to variation in fibrous content.

3.4.1 Methods and materials

Inert waste collected from a landfill in Chiba prefecture was used for this study. Maximum size of the collected inert waste used for this study was 19 mm without any fibrous content. From the particle size distribution as shown in Figure 3.24, the proportions by dry mass of the inert waste (<19 mm without fiber) found as uniformly distributed over specified particle-size ranges of 19 mm – 0.075 mm. Inert waste particles (<19 mm without fiber) were mixed with artificially made fibrous content with the ratio of 'weight' of fibrous content as 0, 0.5, and 1% to prepare the specimens for compaction test and triaxial test. The fibrous content mixed were artificially made by cutting polyethylene woven bags with density of 0.95 g/cm^3, thickness of 0.02 mm, and a size of 25 mm x 2 mm as shown in Figure 3.24.

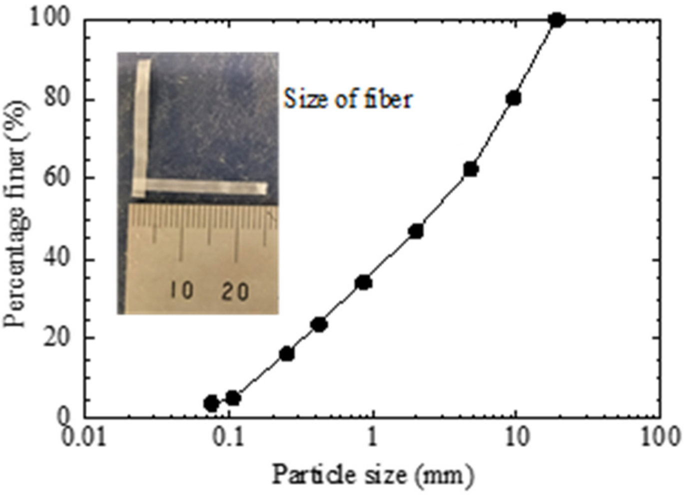


Figure 3.24 Particle size distribution of inert waste

Figure 3.25 Specimen for triaxial test

Compaction test was conducted according to JIS A 1210 to obtain the maximum dry densities and relative optimum water contents of the three specimens with fibrous contents of 0, 0.5 and 1%. After obtaining the maximum densities from the compaction test, triaxial tests were carried out considering 90% degree of compaction on the inert waste specimens containing 0, 0.5 and

1% fibrous content. Each specimen was filled in a mold of 10 cm diameter and 20 cm height, and compacted in 6 numbers of layers with a rammer compacting each layer 25 times. Figure 3.25 shows a specimen for triaxial test during preparation. After preparing the specimens, it was placed in the triaxial apparatus and consolidated drained tests were carried out on the specimen with confining pressures of 30, 60 and 90 kPa. The stress-strain relationship and volumetric change behavior were studied in the triaxial test to confirm the mechanical properties of the inert waste with 0, 0.5 and 1% fibrous content.

3.4.2 Results and discussion

In Figure 3.26, the data for dry densities vs water contents of the compaction test and triaxial test are compared with the data of domestic illegal dumping, oversea waste landfills, and domestic management type landfill data. The data of waste landfills were obtained from the previous study conducted by Yamawaki et al. (2017) and ZAVC was drawn using the average specific gravity of the inert waste from domestic management type landfills. The maximum dry densities obtained in compaction test were 1.68, 1.53 and 1.52 g/cm^3 for inert waste with fibrous content of 0, 0.5 and 1% respectively. The dry densities for 0, 0.5 and 1% fibrous content are shown with grey, green and red colour lines respectively. The degree of compaction for the triaxial test was taken as D = 90% and the dry densities for different fibrous contents were chosen accordingly. The dry densities used for triaxial test with 0%, 0.5% and 1% is shown with grey, green and red colour hexagons respectively. Since, waste material is compacted by heavy trash compactor (30-50 t), the degree of compaction was taken as D = 90% for triaxial test, which made the selected dry densities of triaxial tests closer to the upper values of dry densities obtained in landfill sites. The uniform distribution of the inert waste particles (<19 mm) contributed to the higher density values. With increase in fibrous content, total dry density of the specimen decreased due to two reasons- (a) lower specific gravity value of the fibrous content than the other components present in the inert waste and (b) bulky and bouncy nature of fibrous content making total compaction effect lesser. The dry densities selected for triaxial test were close to the upper values obtained in the inert waste landfill sites.

The changes in the deviatoric stresses with increase in axial strains under confining pressures of 30, 60 and 90 kPa were studied at triaxial test as shown in Figure 3.27. A wide variation in deviatoric stresses were observed with increase in axial strain. The deviatoric stresses increased with increase in confining pressure and fibrous content. Increasing the fibrous content increased the tensile resistance of the inert waste thus increasing the shear stress. The deviatoric stresses showed clear peak values for 0% fibrous content; but as the fibrous content increased, the material behavior changed from “brittle to ductile” and “strain-softening to strain-hardening”. For inert waste with 0% fibrous content, deviatoric stress decreased after a certain axial strain (approximately 3%), but for 0.5 and 1% F.C. the it tended to increase with increase in axial strain and confining pressure. Therefore, for high axial strain cases such as large earthquake etc. inert waste with fibrous content may show higher shear resistance. Figure 3.28 shows the volumetric changes of the three specimens with increase in axial strains under different confining pressures. With increase in axial strain under confining pressures of 60 and 90 kPa, the volumetric change of 0% F.C. showed similar behavior as dense sand and that of 1% was similar to loose sand. The specimen with 1% F.C. behaved like loose sand because as previously explained presence of fibrous content made the density of the inert waste specimen lower. However, in case of confining pressure of 30 kPa, the volumetric changes were showing different trends than that of 60 and 90 kPa confining pressures. The reasons are still unknown and need to be studied.

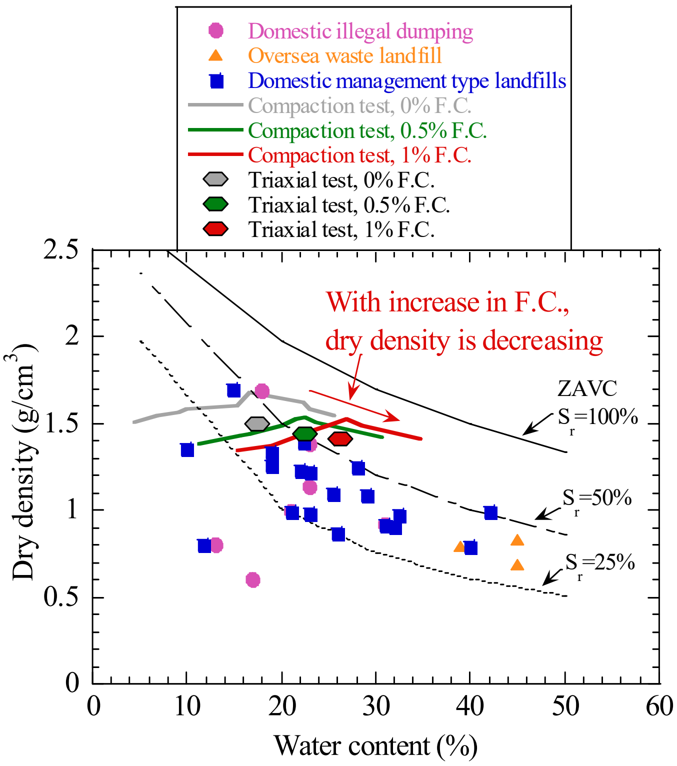


Figure 3.26 Dry density vs water content

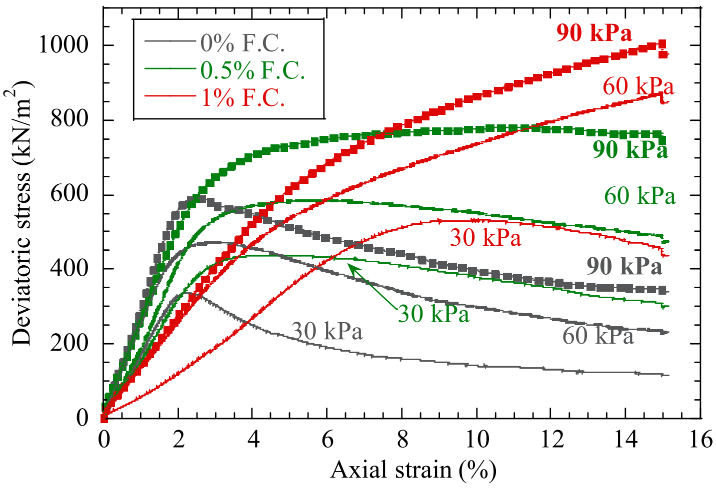


Figure 3.27 Deviatoric stress vs axial strain

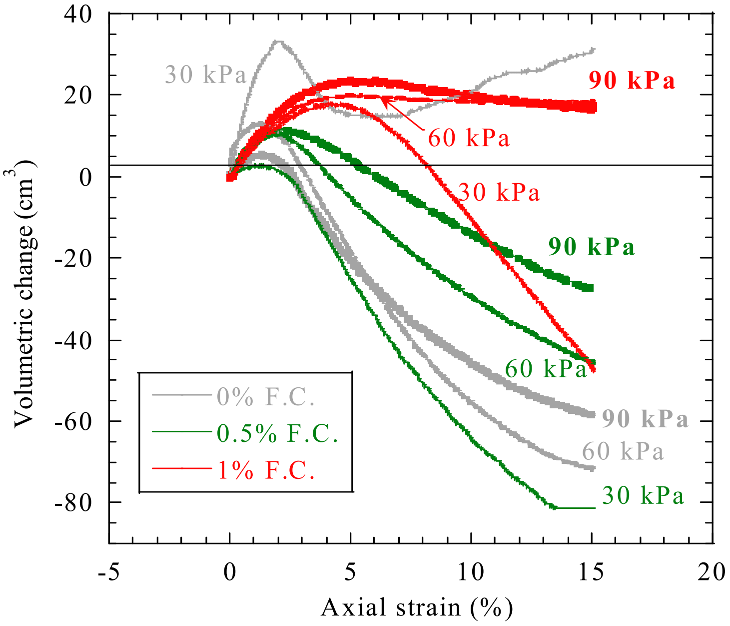


Figure 3.28 Volumetric change vs axial strain

3.5 Conclusions for this chapter

In-situ tests

In this research, strength characteristics and basic physical parameters (such as in-situ density, water content, percentage air voids etc.) of inert waste landfills were studied. Field tests such as composition analysis, basic physical properties, angle of repose, CASPOL impact value test and in-situ direct shear test were conducted at the locations to know mechanical properties of the inert waste materials. From the results of the field tests, the following conclusions could be drawn:

- The inert waste materials were consisting of rocks, glasses, potteries, soil like materials, plastics, other fibers with very little amount of woods and metals. Three main components were found as: 3.6 to 54% of fibrous content (consisting of 'plastics' and 'other fibers' > 20 mm), 13 to 45% of granular content (consisting of 'rocks' and 'glasses and potteries' > 20 mm) and 43 to 74% of soil-like content ($\leq$ 20 mm).
- Increases in soil-like and granular fractions showed significant increase in dry density up to 1.8 times. Dry density decreased with increase in fibrous content under 31%. The change in dry density can be attributed to the specific gravity of different components and bouncy nature of fibrous content which made compaction less effective.
- Percentage air voids was lower for older landfills. With time, settlement increased and voids were filled by water or smaller soil particles or by chemical component/ precipitate formed due to water penetration.
- The water content increased and percentage air voids decreased with increase in fibrous content and age after reclamation. With time, large sized fibrous fractions stored rain water and organic leachate which increased the water content.
- Impact value increased with increase in dry density and soil-like content. Higher the dry density, voids were lesser and bearing capacity became more. Impact value was lower for higher fibrous content and age after reclamation. Decomposition of biodegradable waste and water penetration through the landfill with age after reclamation were considered to be the reason for lower impact value of older landfills.
- For all the locations, angle of repose after avalanche (α_a) was within the range of 34-44°.
- Cohesion values were found within the range of 2-21 kN/m^2 and internal angle of friction was found within the range of 22-59°. The inert waste strength parameters gave higher shear strengths than the municipal solid wastes, particularly for landfills having fibrous fractions ranging from 14% to 31%.
- With increase in dry density, cohesion increased and friction angle decreased.
- The correlation calculated for c and φ with impact value for inert waste landfill within 10 years of age are $c = 4.10\ I_a - 21.32$ and $\varphi = -4.61\ I_a + 82.37$ where, c = cohesion (kN/m^2), φ = internal angle of friction (°) and I_a = impact value. With increase in the impact value, c increased and φ decreased.

- The specific gravity values estimated for fibrous, granular and soil fractions in the inert waste landfills were 1.0, 2.60 and 2.80 respectively.

From this research, a large set of database for inert waste materials at 14 locations of 4 inert waste landfills inside Japan were obtained. There is still a need to do further study on inert waste landfills. Specially, the effect of biodegradable materials present if any, in the inert waste landfill should be properly studied. We should also check, if there is any water storage by large plastics etc. inside the landfill or any contamination from the waste materials of the landfills. Leaching tests can be performed to check these issues.

Laboratory direct shear test

In this research, the effect of fibrous fractions on shear strength properties were evaluated by laboratory direct shear tests. The internal friction angle first increased, then decreased with an increase in the proportion of fibrous materials to a certain extent and the cohesion first decreased and then increased. But these observations were highly depended on the samples. It is assumed that heterogeneity in basic property (e.g. size and shape) of inert wastes played a significant role in these variations of results. For this research, the effect of size of inert waste on strength property was difficult to be considered because composition analysis based on size of inert waste was not conducted. But size of inert waste is important to evaluate the strength property of waste ground, so it is necessary to evaluate the strength property on consideration to basic property of inert waste. In the future, test results can be obtained considering more detailed basic properties of the samples to evaluate above observations significantly. A thorough study of the scale effect of the direct shear test should also be carried out in the future.

Laboratory triaxial test

Dry densities of inert waste decreased with increase in fibrous content. Bouncy nature of fibrous content made the compaction less effective and lower specific gravity of fibrous content than other components made a decrease in the dry density. In triaxial test, deviatoric stresses increased with increase in confining pressure and fibrous content. With increase in axial strain under confining pressures of 60 and 90 kPa, the volumetric change of 0% F.C. showed similar behavior as dense sand and that of 1% F.C. was similar to loose sand. For 0.5% and 1% fibrous content under high confining pressure, deviatoric stress increased after a certain axial strain. Therefore, under high axial strain condition, inert waste with fibrous content may show higher shear resistance. The results obtained in this study are useful for slope stability analysis and dynamic analysis of the inert waste landfills.

Chapter 4
Leaching characteristics

4.1 General remarks

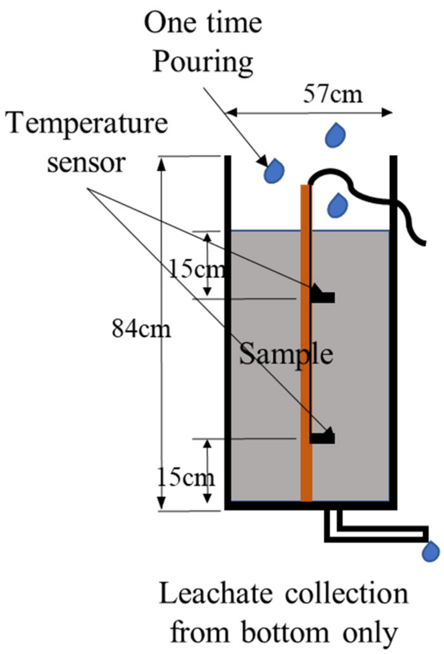
Though inert waste should contain chemically inert materials, still there are some possibilities of presence of contaminants in those waste (USEPA, 1998). Due to human negligence or some inevitable conditions, there may be a mixing of biodegradable materials with the inert waste. Arsenic (As) may be naturally present in the soil excavated in the landfill sites. Glass and ceramic etc. may contain excessive boron (Brookins, 2012). Presence of other heavy metals such as Pb, Cr, Cu, Zn etc. in the construction and demolition waste was previously confirmed by many researchers. Therefore, leachate generated in the inert waste landfills may be contaminated with all these contaminants, and if they are mixed with the groundwater, surface water or nearby soil area at an excessive rate, that may cause water pollution as well as soil pollution in the neighborhood. There is also a possibility of storage of leachate by the plastics inside the inert waste landfill, thus enhancing the risk of contamination. Storage of leachate may also reduce the strength and stability of the landfill. Leaching tests are best options to check the safety from the landfill leachate. There are various kinds of leaching tests which include column tests, batch tests, lysimeter tests and sequential leaching tests. Lysimeter test and column test resemble the field conditions more than the batch test, and it is suitable for determining the long-term release of chemical constituents into the water bodies (Naka et al. 2016). In this research, lysimeter test, laboratory column leaching test, and laboratory batch leaching test were conducted to understand the leaching behavior of inert waste collected from different landfill sites in Japan. Lysimeter test was conducted to know the leachate behavior of the inert waste collected from the landfill sites where the size of the inert waste was the same as the site. Laboratory column tests were carried out to compare the results of lysimeter leaching test and to conduct some deep research with some specific conditions as it gives control over the operation, monitoring and sample collection. Laboratory batch leaching test was conducted for a quick analysis of the leachate quality before using it in laboratory columns. Another reason for carrying out the lysimeter, laboratory column and batch leaching tests is the controversy that still exists in the literature on the representativeness of the results from laboratory and field tests (Delay et al. 2007 and Lind et al. 2008). Moreover, the small scale column in the laboratory is easy to design and operate, and effective for estimating the field leaching behavior for a wide range of materials under both disposal and use conditions (Kosson et al. 2014).

4.2 Large scale lysimeter leaching tests

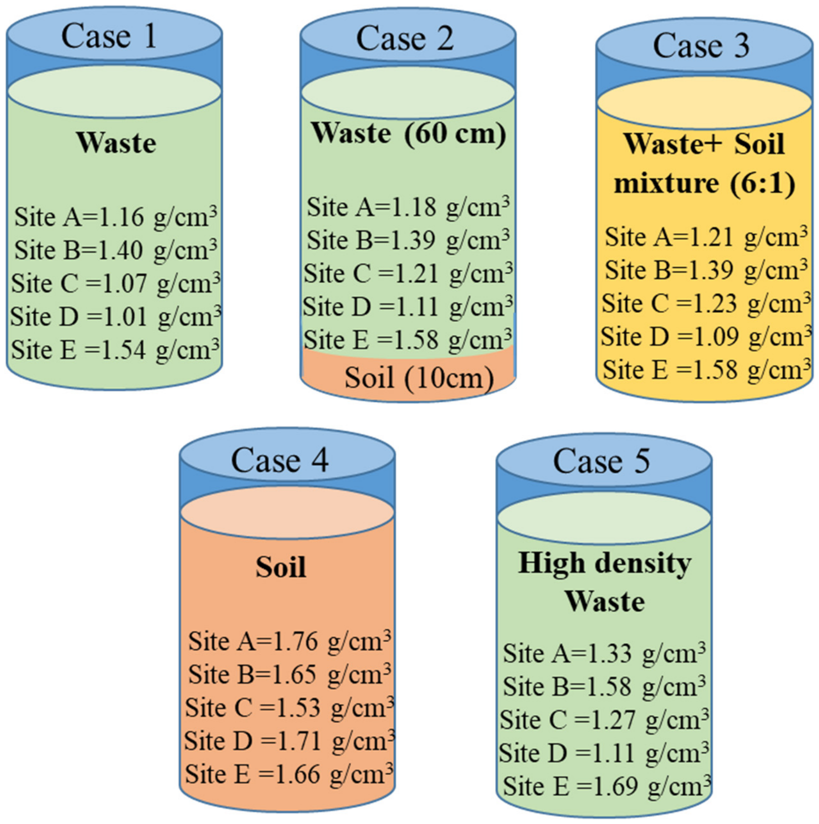
Large scale lysimeter tests were performed to understand the leachate behavior of inert waste, and sorption capacity and buffering effect of cover soil collected from the inert waste landfill sites. In lysimeter tests, the size of the waste was kept same as the size found in the sites, which was significant, because it assisted understanding the leachate behavior of the inert waste materials at a similar condition as in the inert waste landfills. Water storage due to large fibrous fractions etc. and the possibility of contamination were studied for one year. Samples were collected from five inert waste landfill sites, and for each site, five cases were made which were waste, waste with soil layer, waste and soil mixture, only soil, and high-density waste.

4.2.1 Methods and materials

The inert wastes and cover soil collected from five sites were named as A, B, C, D, and E and were used for lysimeter leaching test. The lysimeters had a diameter of 57 cm and a height of 84 cm. The sizes waste materials used in the lysimeter tests were kept the same as obtained in the sites. Each of the lysimeter had a close-fitting cover which could be closed after pouring the input water. Moreover, the lysimeters were placed below a covered area to keep them safe from the influence of heavy rainfall. The wastes were compacted in three layers of 20 cm each. Table 4.1 shows conditions of five cases for lysimeters and their evaluated parameters. The outline of lysimeter and compacted conditions for lysimeters of all the sites are also shown in Figure 4.1. Case 1 was the lysimeter with only waste. Case 2 was made of waste with soil layer below the waste to evaluate buffering effect and heavy metal and organic pollutant sorption effect of soil layer. Case 3 was the mixture of soil and waste at a rate of 6:1 on volume basis. This case was done to evaluate effect of waste-soil mixture on sorption and percolation property. Case 4 was made with only soil to evaluate leachate flow property and quality of leachate through soil layer. Case 5 was made with highly compacted inert waste compared to case 1, to evaluate the effect of highly compacted reclamation on leachate flow property and quality of leachate. Densities of case 1 ~ 4 were almost the same as an on-site value, and density of case 5 was approximately 1.1 times larger than the in-situ value. The density of the case 3 was assumed as the value obtained, when waste and soil with site densities were mixed at a rate of 6:1.



(a) Lysimeter outline



(b) Lysimeter cases

Figure 4.1 Lysimeter leaching test outline and cases

Table 4.1 Conditions of five columns and evaluated item

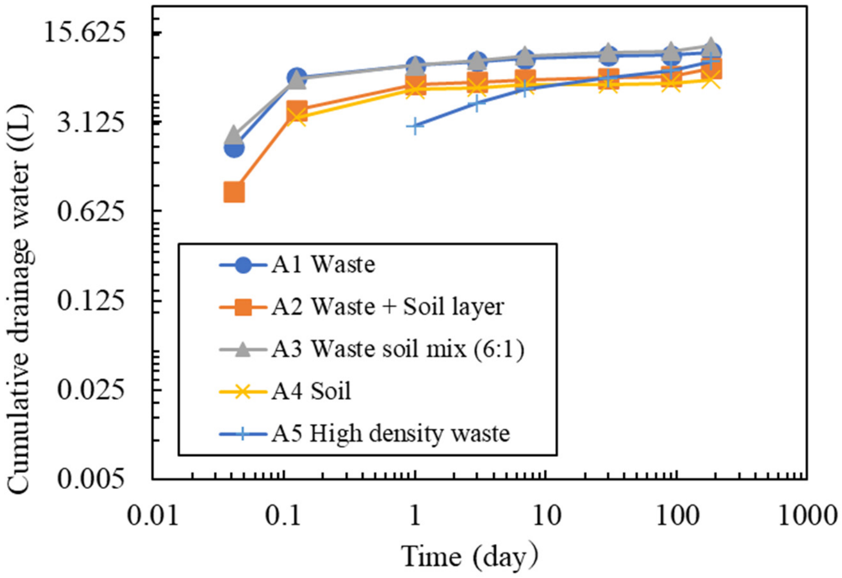
Column	Samples	Height (cm)	Parameters measured for quality of percolated water	Measurement of gas	Measurement frequency
Case 1	Waste	60	pH, EC, TN, TOC, Pb, As, SO_4^{2-}, SS	H_2S, CH_4	1st day 1 month 3 months 6 months 1 year (amount of drainage water was measured every sampling)
Case 2	Waste + Soil	Waste: 60 cm Soil: 10 cm			
Case 3	Mixture of waste and soil	70 cm (waste: soil as 6:1)			
Case 4	Soil	60 cm			
Case 5	Waste (highly compacted)	60 cm			

The way of water pouring and sampling was same throughout all cases. 12.6 liters of water was poured in 30 minutes from surface evenly using watering pot. Collection of leachates was done from valve attached on bottom. Leachate collection intervals were 1 minute till 1 hour, then 10 minutes for 2 hours, after that 30 minutes for 3 hours continuously. In case when it took several hours from pouring to drainage, then sampling intervals were 1 minute till 1 hour, then 10 minutes till 3 hours and after that 30 minutes till 6 hours from drainage starting. After finishing collecting the leachate, the top of the column was covered, and the bottom valve was closed to prevent the evaporation of water in the column. Sampling intervals after that were same throughout all cases: after 24 hours, after 3 days, after 1 week, after 1 month, after 3 months, after 6 months, and after 1 year with valve opened for 30 minutes for each sampling.

4.2.2 Results and discussion

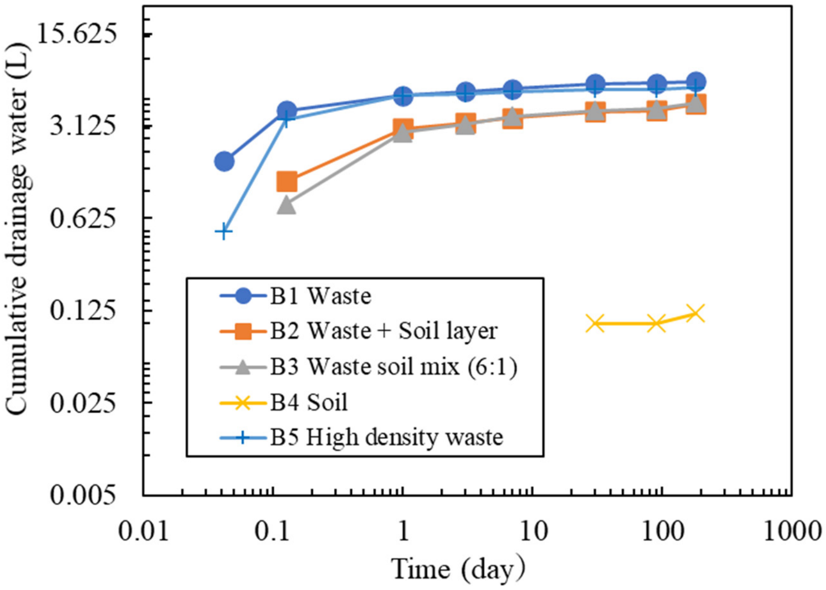
Figure 4.2 shows the continuous change of cumulative drainage water with respect to time for the columns with waste from site A (0.1-year-old ground), site B (19-year-old ground), site C (0.6-year-old ground), site D (10-year-old ground), and site E (2-year-old ground). The drainage through the waste lysimeters were seemed higher than the waste with soil layer or only soil lysimeters except site D and site E. Lower density of waste than soil made the drainage higher in case of waste lysimeters. For case D and E, storage of leachate in large size of fibrous fractions present in the waste may be the reason of low drainage through waste lysimeters. The mixture of waste and soil showed different drainage behaviors than the only waste or only soil.

Thus, retention property of percolation water is dependent on reclamation method. For site E lysimeter, the drainage started later than the other cases, so little amount of drainage were obtained. In case of high-density waste, the drainages were lower than the regular waste for lysimeters A, B, and E. From the mechanical characteristics of inert waste, it was clear that with higher density, the fibrous content was less and soil like content and granular content were more in the inert waste materials. In the case of high-density waste, the interlocking of the materials was better, thus making the voids less. Therefore, the lesser number of voids resisted the drainage, and the probability of preferential flow of water was reduced. However, for lysimeters C and D, high-density waste showed higher drainage than regular waste. The reason for this behaviour is supposed to be the composition of the waste materials. From the inert waste landfill data, the fibrous content in landfills C and D were higher than that of A, B, and E. Therefore, even with high density, there were more voids present in the lysimeters due to the presence of the higher fibrous fractions. From this result, it is clear that the storage of water in large fibrous fractions is possible even with low fibrous content if the number of voids present in the inert waste is less. On the other hand, in the case of high fibrous content in the inert waste, there may be less storage of water if the waste is in loose condition. In that case, the increase in the number of voids escalate the drainage of water through the voids and also sometimes generates preferential flow.

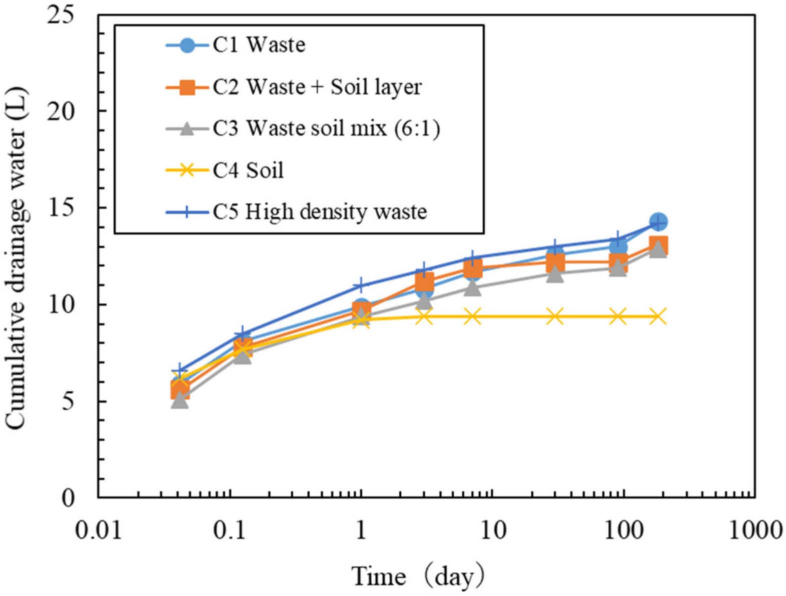


(a) Site A (0.1-year-old ground)

Figure 4.2 Drainage conditions of lysimeters

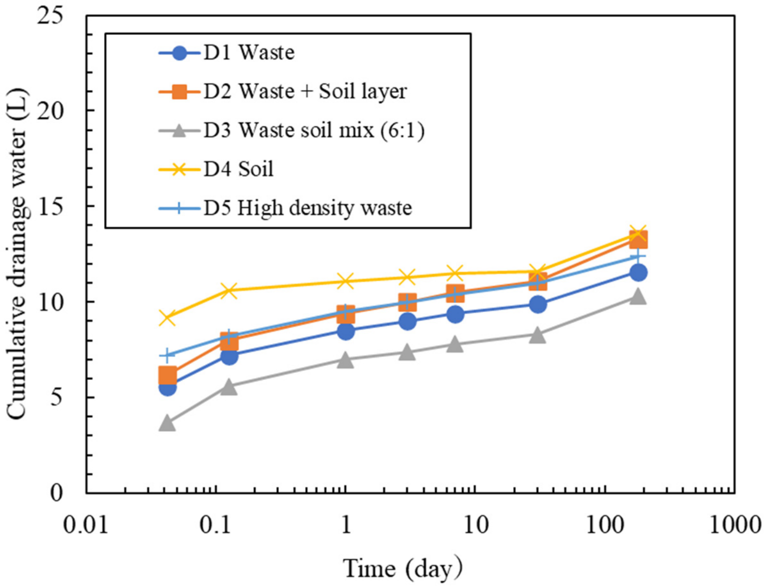


(a) Site B (19-year-old ground)

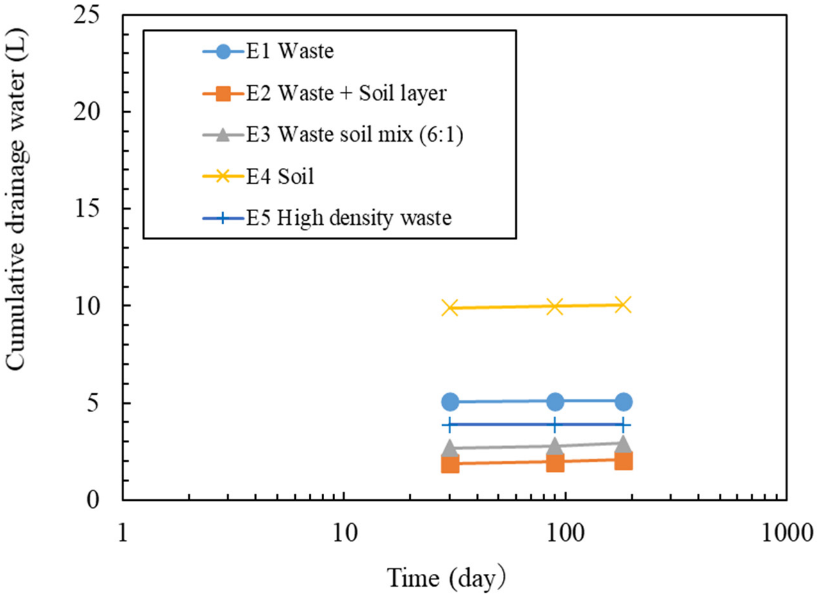


(b) Site C (0.6-year-old ground)

Figure 4.2 Drainage conditions of lysimeters



(c) Site D (10-year-old ground)



(d) Site E (2-year-old ground)

Figure 4.2 Drainage conditions of lysimeters

Figure 4.3 shows the relationship between the cumulative dissolved total organic carbon (TOC), total nitrogen (TN), Sulfate ion (SO_4^{2-}) with respect to the liquid-solid ratio (L/S) for sites A and B. From Figure 4.2 it was observed that retention property of leachate is dependent on reclamation method and this leads to variation in liquid-solid ratio for different columns. Hence, at this stage it was difficult to compare the cumulative dissolved parameters for different cases as all of them had different liquid-solid ratio. This issue was resolved by extrapolating the graphs of liquid-solid ratio (L/S) vs. dissolved parameters. From the graph for columns of site A, for the case A4, the dissolved TOC and SO_4^{2-} was very less or negligible. For the cases A2, A3 the dissolved parameters were lesser or almost equal; and in case A5, parameters were higher or almost equal in comparison to case A1. The graphs for site B also showed similar trends. From these observations, sorption of dissolved toxic materials present in the leachate by the soil under waste layer and mixed into waste was confirmed. Therefore, the soils obtained from the excavation work during the construction of a landfill can be easily used to improve the leachate quality. An increase in concentration of dissolved toxic materials in percolation water was observed from highly compacted reclamation, but the parameters were found within the standard limit.

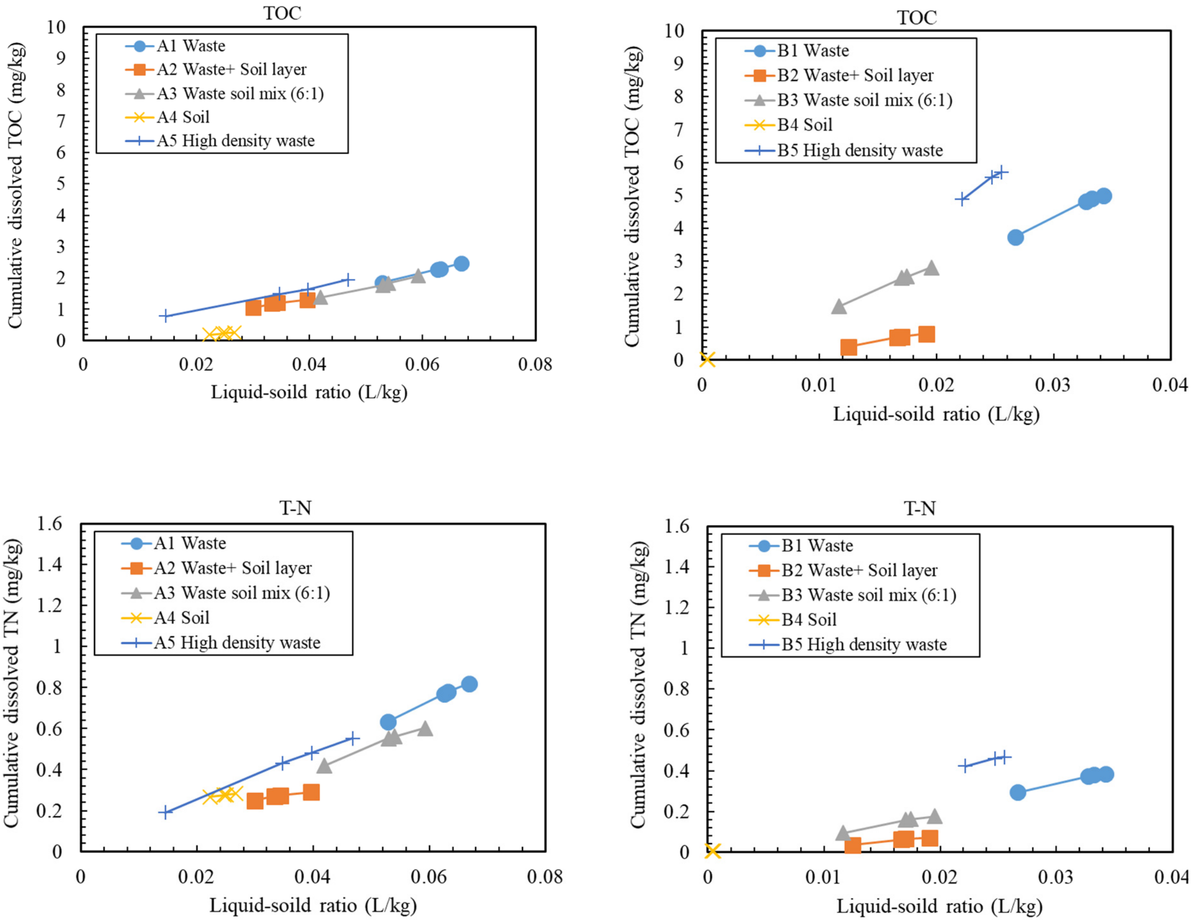


Figure 4.3 Change in toxic parameters of leachate with increase in L/S ratio of lysimeter

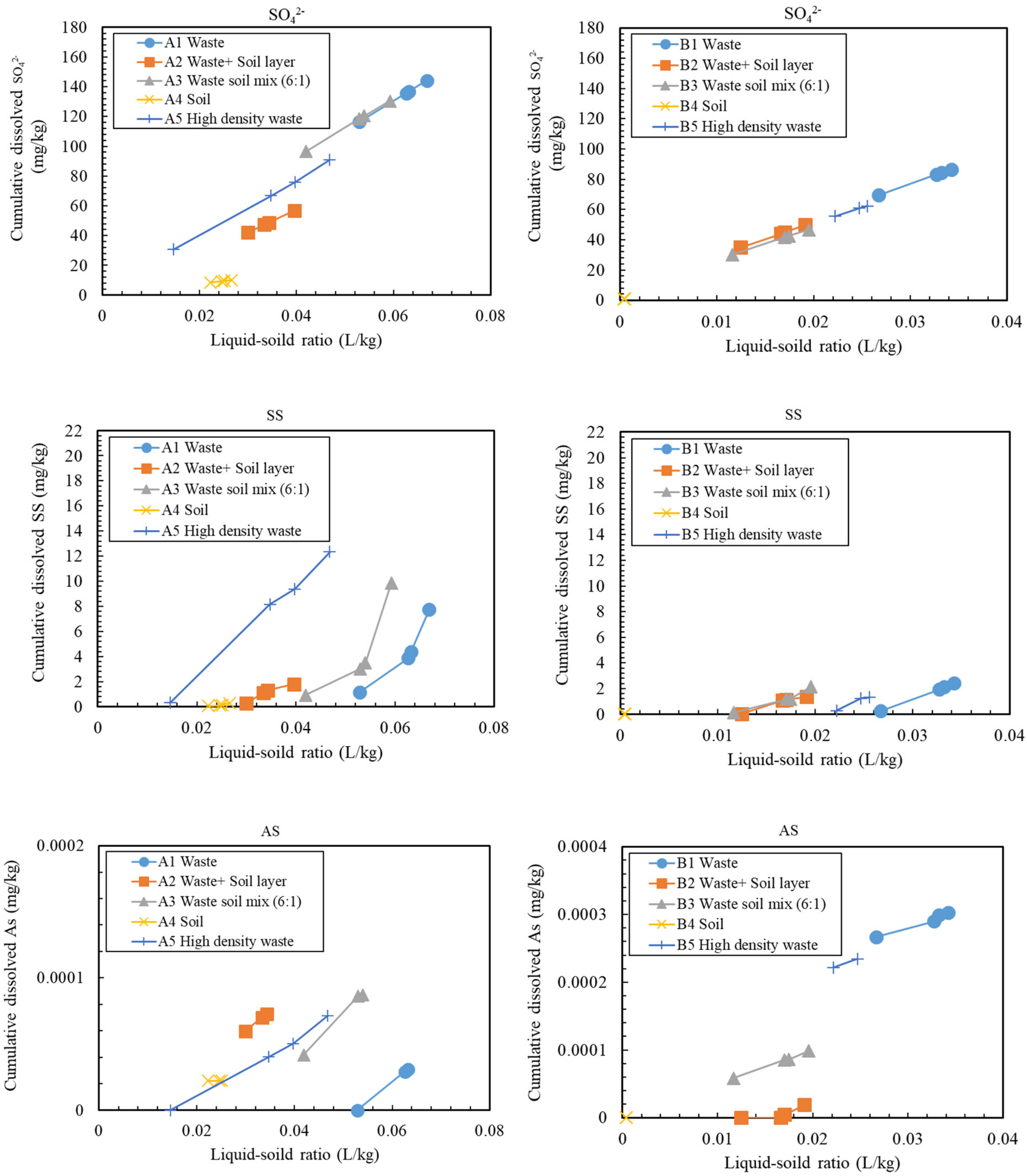


Figure 4.3 Change in toxic parameters of leachate with increase in L/S ratio of lysimeter

4.3 Laboratory column leaching test

The laboratory column leaching test was conducted to confirm the representativeness of the results of lysimeter with control over operation, monitoring and sample collection. The main objective of the laboratory column leaching test are

a) To observe the effect of variation in small-sized fibrous fractions (<5 cm) on the leachate storage inside the inert waste landfill with the help of moisture sensors.

b) To evaluate the difference in concentrations of contaminants such as heavy metals and TOC due to variations in fibrous content in the inert waste and to observe the leaching behavior with variations in pH, Redox condition (Eh), Electrical conductivity (EC).

c) To study effectiveness of soil layer (reduced 25% than the lysimeter cases) in sorption and acid buffering of leachate.

4.3.1 Methods and materials

For this test, two columns with fibrous content of 2% and 10% were prepared. The inert waste materials for the columns were collected from location D1 in Chiba landfill. The columns used for this research had a diameter of 30 cm and a height of 100 cm. First, the fibrous fractions were separated from the inert waste. The waste materials were then sieved with a 5 cm x 5 cm size sieve because of the size restriction of the columns. The size used for the column waste materials was less than 1/4th of the column diameter. After sieving, waste materials were thoroughly mixed to confirm the reproducibility in both the columns. After mixing, two samples were prepared by adding fibrous fractions of 2% and 10% with size ≤ 5 cm to the mixer of inert wastes. The two columns were then filled with the two samples in 4 numbers of layers with equal compaction energy. To check the water storage, moisture sensors were installed at two points of 15 cm and 55 cm from the top waste layers for both the columns. Thermometers were also installed at the same points to check the temperature variation. As in the landfills, where we use soil layers for reclamation, in these columns, an additional soil layer of 10 cm at the bottoms of the columns were provided to make the leachate quality better. The leachate collection points were at 40 cm and 80 cm from the top of the waste layer, (both above the soil layer) and at the bottom of the columns (below the soil layer). The soil layer was made with decomposed granite soil sieved with size 2 mm. The design parameters for laboratory column leaching test are shown in Table 4.2. The waste density and waste moisture content were different for both the columns. In the column with high fibrous content, the density was lower. It was obvious because of the low particle density of the fibrous fractions. The moisture content was also less in case of high fibrous content because the soil fractions in the column with low fibrous content absorbed more water which made the water content higher.

Table 4.2 Design parameters for laboratory columns

Parameters	Column 1	Column 2
Waste fibrous content	2%	10%
Waste layer	80 cm	80 cm
Soil layer	10 cm	10 cm
Waste density	1.38 g/cm^3	0.92 g/cm^3
Soil density	1.88 g/cm^3	1.88 g/cm^3
Waste moisture content	9.39%	3.76%
Water pouring	Every 5 days	Every 5 days
Rainfall	1530 mm/year	1530 mm/year
Leachate collection	3 points	3 points

Figure 4.4 shows the various steps followed for the preparation of column. The columns with moisture sensors were first tested with soil before putting waste into the column. The moisture sensors were calibrated before using them in the columns. The procedure for sensor calibration is given below

Volumetric water content is calculated by the equation below

$$\theta = ((\sqrt{\varepsilon}) - a_o)/a_1 \ldots\ldots (4.1)$$

Here, a_o and a_1 are the constants we need to find by calibration and

$$\sqrt{\varepsilon} = 1.0+14.4396V-31.2587V^2+49.0575V^3-36.5575V^4+10.7117V^5 \ldots\ldots (4.2)$$

Where, V= SM150 output in Volts,

$a_o = \sqrt{\varepsilon_o}$ as $\theta_o=0$ (for dry sample),

$a_1 = ((\sqrt{\varepsilon_w}) - (\sqrt{\varepsilon_o}))/(\theta_w - \theta_o)$,

$\theta_w = (W_w - W_o)/L_s$,

W_w= Weight of wet sample,

W_o= Weight of dry sample,

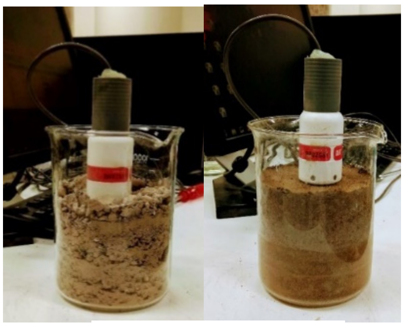
L_s= Volume of the wet sample

The calibration results are shown in Table 4.3. The waste and soil had different a_o and a_1 values. Using these values obtained for waste, the volumetric water content was calculated.

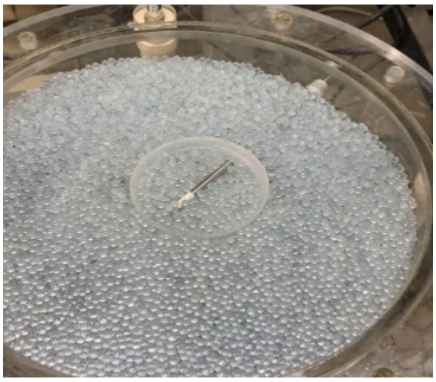
Table 4.3 Calibration results for waste and soil

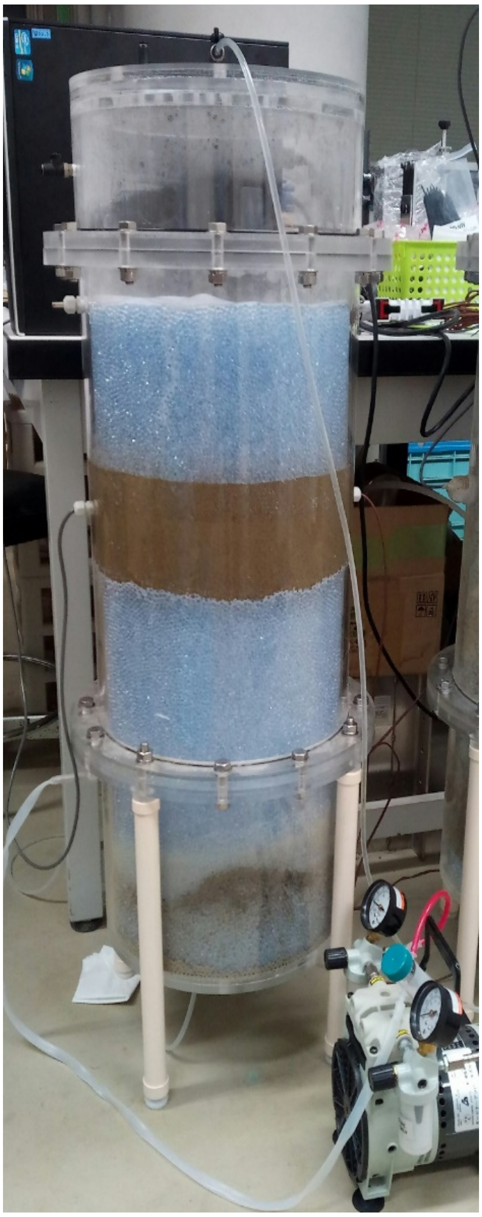
Type	a_0	a_1
Waste	1.48	6.88
Soil	1.69	8.42

Sieving



Sensor calibration





Placing leachate collection tube in column

Test column with only soil layer

Figure 4.4 Various steps followed for the preparation of column

Compaction energy applied for preparation of column

$$\frac{Hammer\ weight\ x\ height\ of\ drop\ x\ blows\ per\ layer\ x\ number\ of\ layers}{Volume\ of\ waste}$$

$$= \frac{9\ kg\ x\ 9.81\ (m/s^2) x\ 0.1m\ x\ 100\ x\ 4}{\pi/4 x\ (0.3\ m)^2\ x\ 0.8\ m}$$

$$= 62.45\ kJ/m^3$$

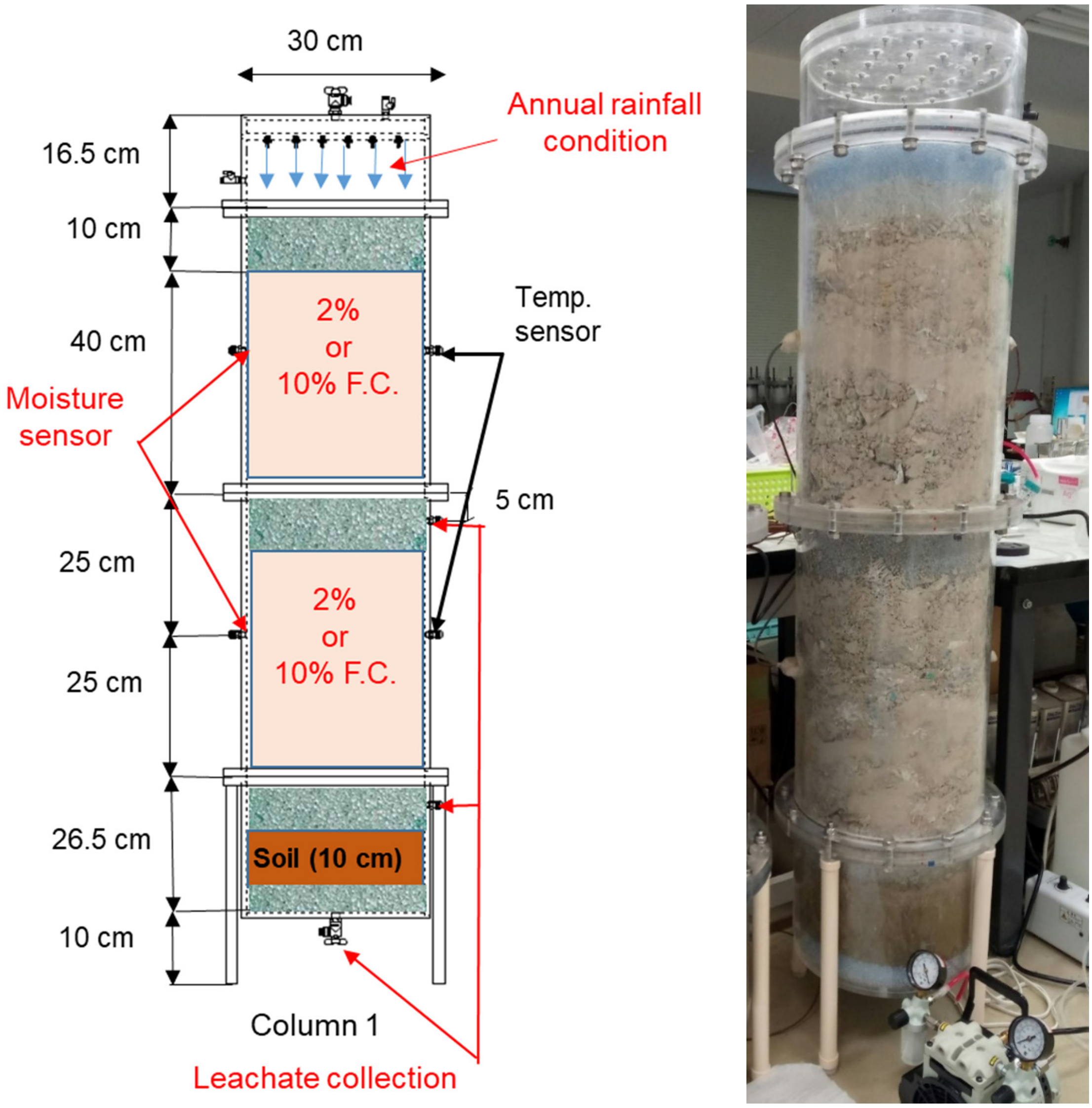
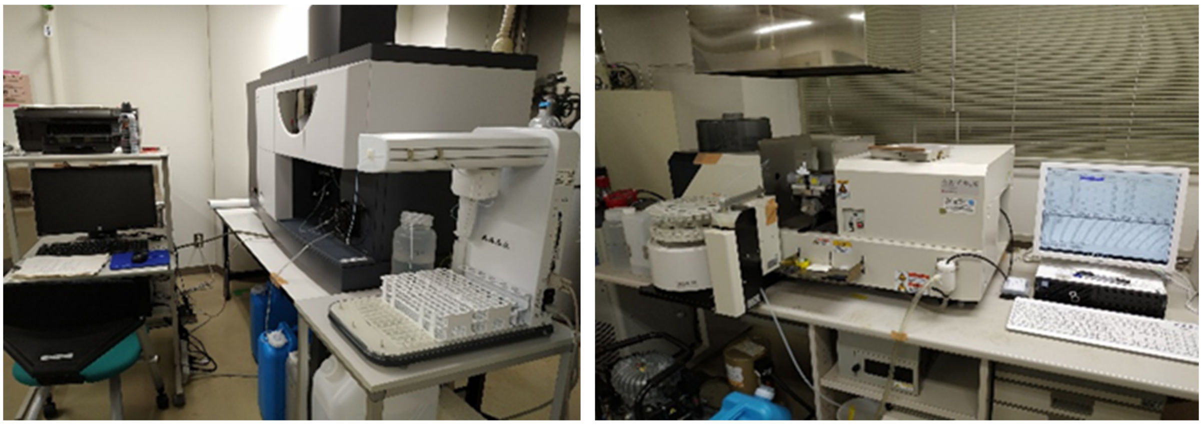


Figure 4.5 laboratory column outline

The final prepared laboratory column with all configuration is shown in Figure 4.5. Water was applied on the top of the column and quantity of the water was taken as the average annual rainfall in Japan (1530 mm). Leachates were collected at the bottom below the soil layer (leachate of waste with soil layer), 80 cm and 40 cm from the top of the waste layer (both above the soil layer) in the column. After centrifuging, they were filtered and analyzed for pH, EC, Eh, total organic carbon (TOC) and other ions and metals. Total Organic Carbon Analyzer (TOC-5050A) was used to measure the total organic carbon in the leachate. To measure the ions and metals in the leachate, ICP-OES series 700 and Atomic Absorption Spectrophotometer, AAS (AA-6800) were used. Figure 4.6 shows the various machines used to analyze the quality of leachate.

(a) Centrifuge machine

(b) TOC-5050A



(c) ICP-OES series 700

(d) AAS (AA-6800)

Figure 4.6 Various machines used to analyze the quality of leachate

4.3.2 Results and discussion

Comparison of storage in lysimeter and laboratory columns

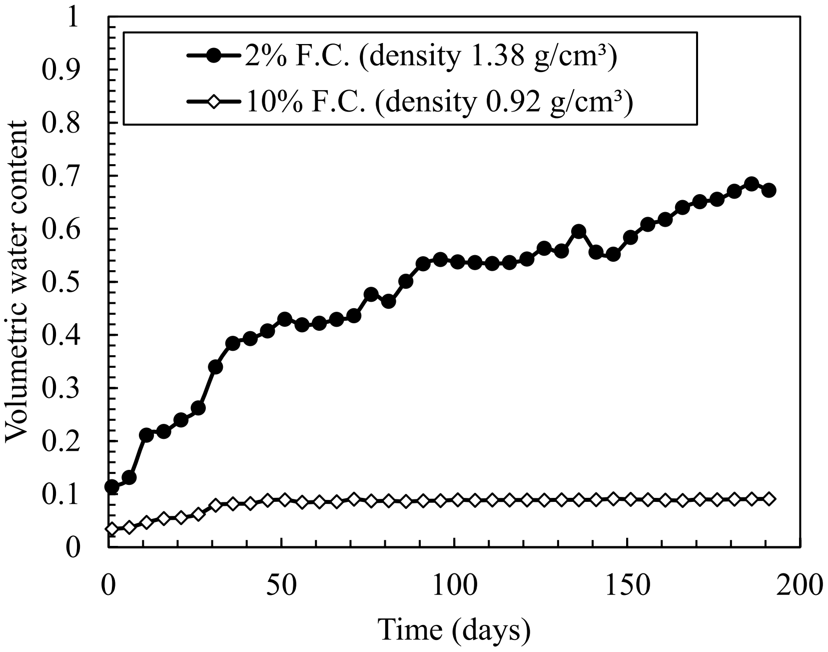


Figure 4.7 VWC in two laboratory columns (sensor)

The water storage inside the column were checked moisture sensors. Figure 4.7 demonstrates the change in volumetric water contents with change in time for the columns with 2% fibrous content and 10% fibrous content. The water storage was lesser for the column with higher fibrous content (10%) or less density. This result shows a good agreement with the lysimeter storage results. The high fibrous content makes the density of the waste material lower inside the column. There are more voids which are connected to each other thus making the flow of water faster and more. The possibility water storage on the fibers was also less for this case due to the small size of the fibrous fractions (5 cm x 5 cm). Figure 4.8 shows water storage in five cases of lysimeters. The water storage was calculated by subtracting the cumulative drainage from the total input water. The five cases of lysimeters had different densities. It was observed that with increase in density of the inert waste material, the storage of water increased or the drainage of water decreased. Possible reasons for high storage may be due to the lesser voids present in high density materials.

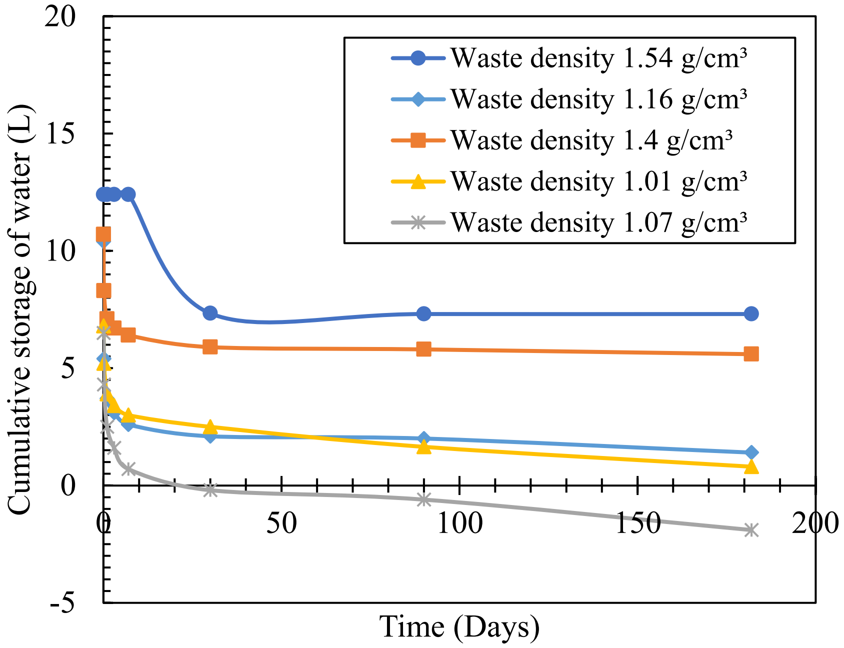
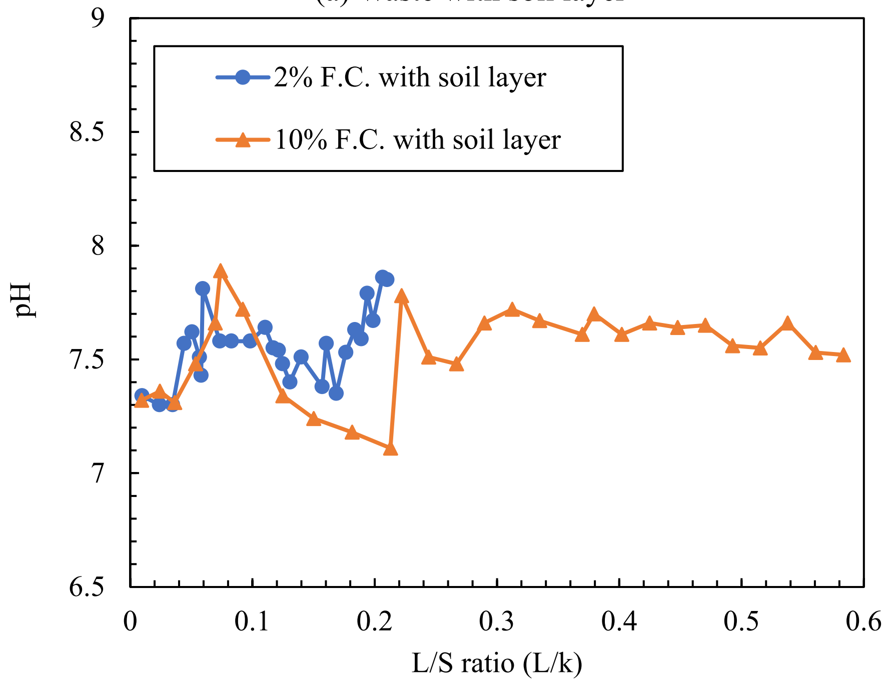


Figure 4.8 Water storage in five cases of lysimeters

pH and temperature

The leachate collected below the soil layer was also analyzed for pH, electrical conductivity (EC), redox potential (Eh), total organic carbon (TOC), ions and other metals. The leachate was slightly alkaline in nature. Figure 4.9 shows change in pH with an increase in the L/S ratio. The pH was higher for waste above the soil layer than waste with soil layer and it gradually decreased. For waste with soil layer, the pH value was first around 7.4 and it gradually increased with L/S ratio. For waste above the soil layer, the pH value was around 8.3 at first and then it started to reduce with time. The soil layer showed buffering capacity, which decreased with increase in the L/S ratio. Figure 4.9 shows the change in pH for two columns with and above the soil layer. The temperatures at the top portion and the bottom portion for both columns are shown in Figure 4.10. With increase in time, temperature first increased and then decreased. It is because with increase in time, the contact of inert waste and water increased and heat generated due to the reaction between the chemicals and water. This made an increase in the temperature.


(a) Waste with soil layer

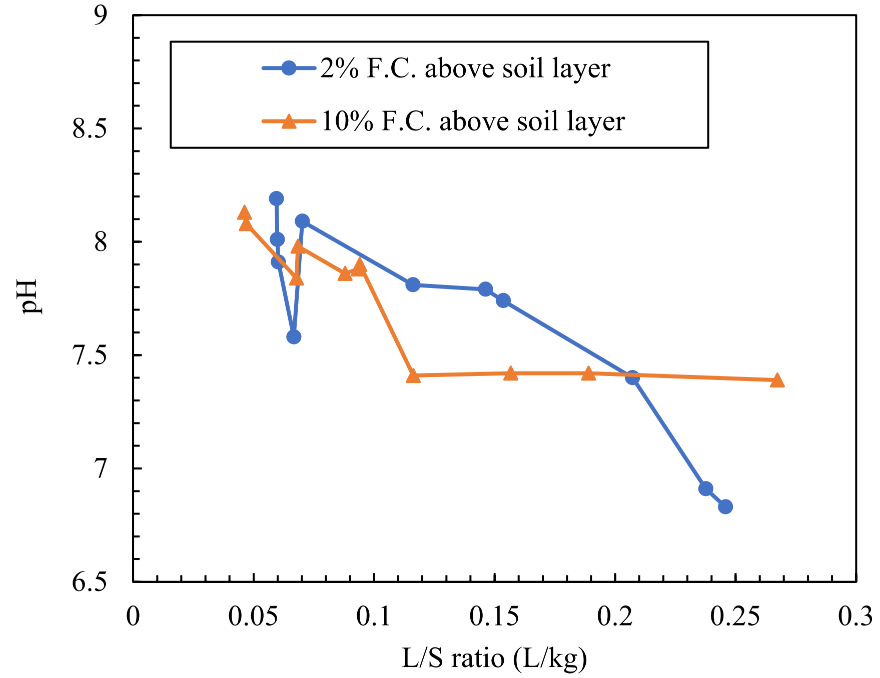

(b) Waste above soil layer

Figure 4.9 Change in pH with increase in L/S ratio

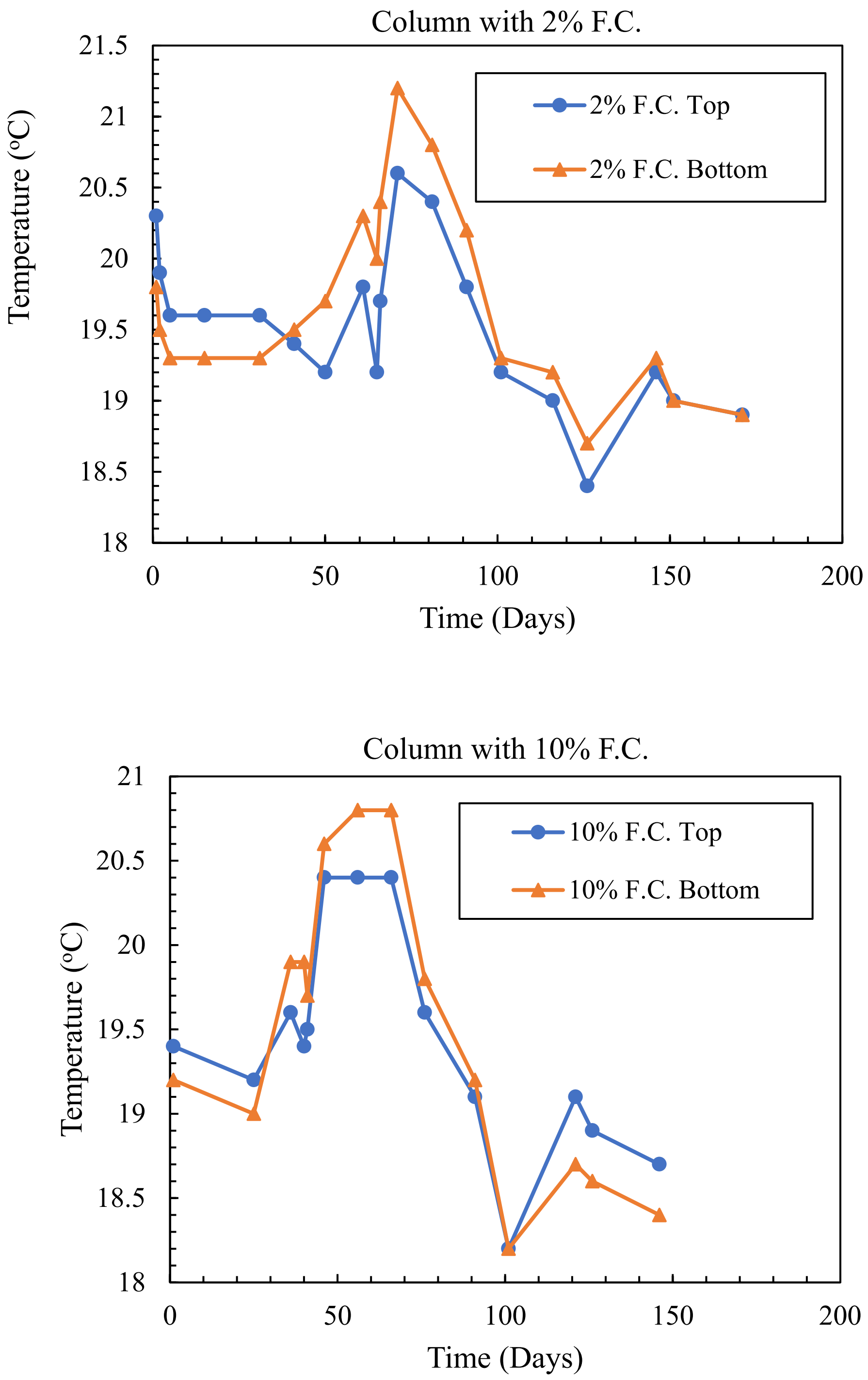


Figure 4.10 Change in temperature with increase in time

EC

Figure 4.11 shows the change in electrical conductivity (EC) with an increase in the L/S ratio. The EC for the column with 2% fibrous content was higher than EC of 10% fibrous content. In case of 10% fibrous content, due to the less density of the waste material, the flow was higher making the water contact time lesser. Therefore, the leachate from 10% fibrous content column contained lesser ions. Due to longer contact time of water with the waste, for 2% fibrous content, the ions present in the waste materials were precipitated or absorbed by the soil layer. Whether in case of 10% fibrous content, the ions do not get much time to have sorption in the soil layer or to get precipitated due to the high drainage of water and less water contact time. Waste with soil layer had almost half value of Electrical Conductivity (EC), which indicates the sorption behavior of soil.

Eh

Figure 4.12 shows the change in Eh with an increase in the L/S ratio. The redox capacity (Eh) was found fluctuating between 450 to 350 mV. The use of soil layer did not show much change in the Eh value. The waste was considered as moderately reduced with Eh range of 300-400 mV (Kamon et al. 2002).

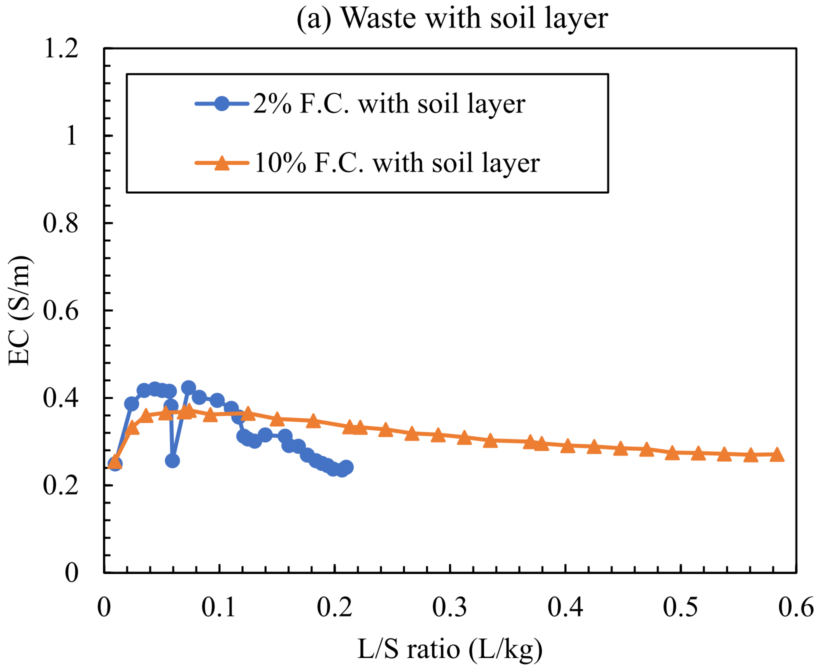


Figure 4.11 Change in EC with increase in L/S ratio

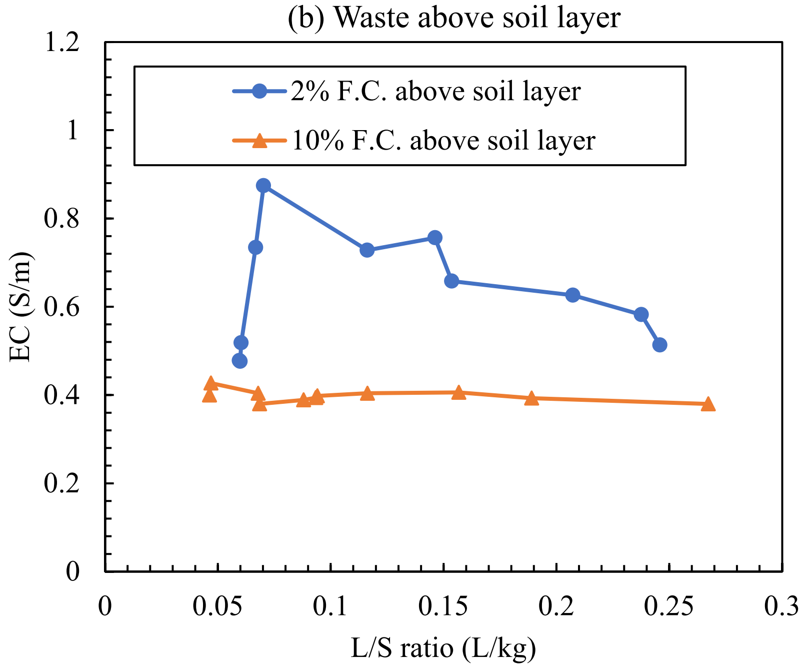


Figure 4.11 Change in EC with increase in L/S ratio

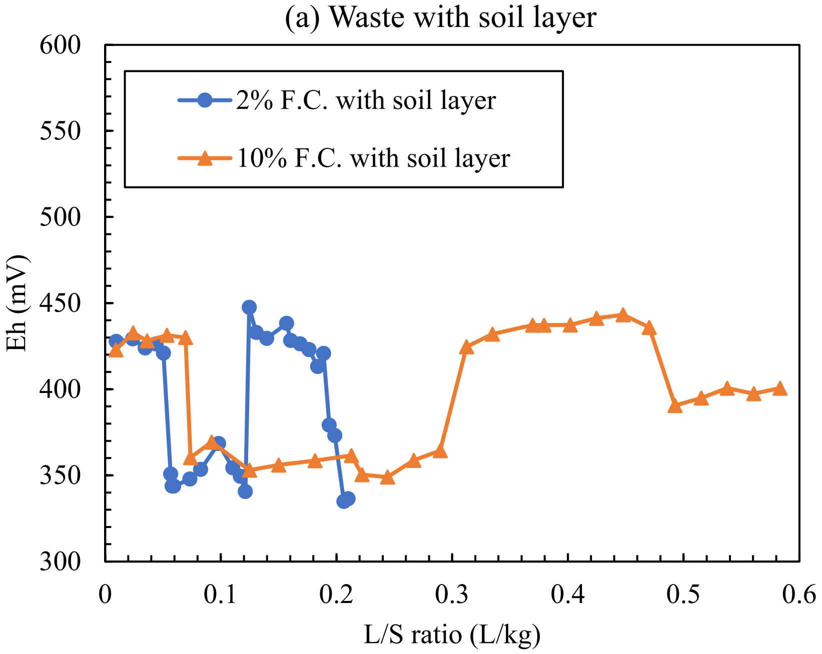


Figure 4.12 Change in Eh with increase in L/S ratio

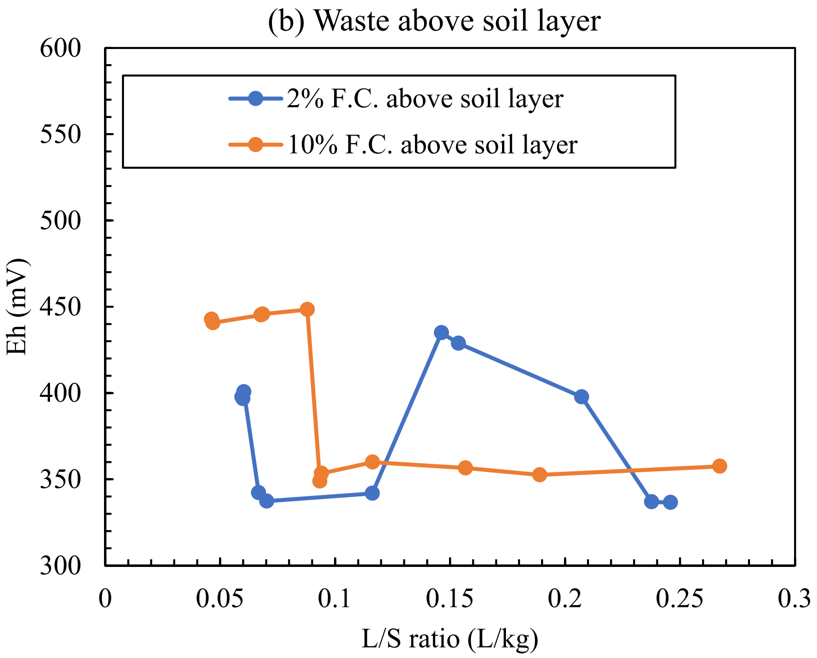
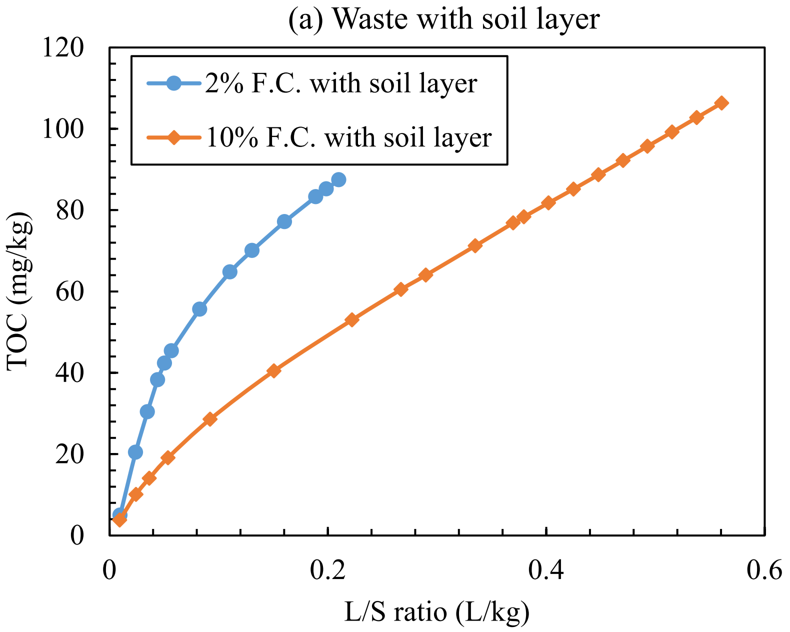


Figure 4.12 Change in Eh with increase in L/S ratio

Total Organic Carbon (TOC)

The colour of the inert waste became black, and it continued to darken with time. It was a sign of the presence of organic matter with the inert waste. After the analysis, total organic carbon (TOC) was found in the inert waste material. This result confirmed the mixing of biodegradable materials with inert waste materials. Figure 4.13 shows the change in TOC with L/S ratio for column with 2% fibrous content and for column with 10% fibrous content. Although the TOC confirms the presence of biodegradable material in the inert waste, the limit of TOC was found to be far lower than the standard limit. The TOC for the column with high fibrous content (10%) was lesser than the TOC from the column with less fibrous content (2%). It means, the waste materials other than fibrous fractions contains more biodegradable materials. The high drainage of leachate within short time period and less contact time of water are other reasons of lesser TOC value in case of higher fibrous content (10%). Use of soil layer was effective as it reduced the TOC more than 50%.


(a) Waste with soil layer

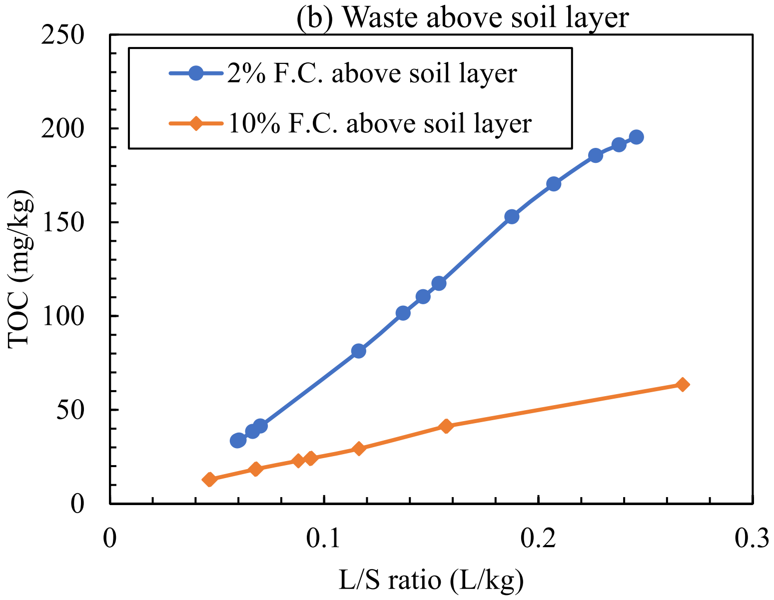

(b) Waste above soil layer

Figure 4.13 Change in TOC with increase in L/S ratio

Heavy metals Arsenic (As), and Boron (B)

The heavy metals As and Boron were found in the leachate of the inert waste materials. The naturally contaminated soil may be the source of As in the inert waste materials. Boron was assumed to come from the glasses and ceramics. Changes in As and boron with increase in L/S ratio are shown in Figure 4.14 and 4.15 respectively. As and Boron were >50% lower for high fibrous content (10% F.C.) than low fibrous content (2% F.C.). Higher drainage of leachate within short time period and presence of lower amount of granular and soil content in high fibrous content released less As and boron. Although the limits of As and boron were found higher than the standard limit, decreasing trends of As and boron with L/S ratio was observed. Because soil layer removed about 50% of As and Boron by sorption even the thickness of it was reduced 25% than the lysimeter. From this result, the quality of the inert waste can be considered as safe for the environment. Moreover, reclamation with soil layer can be considered as a better approach.

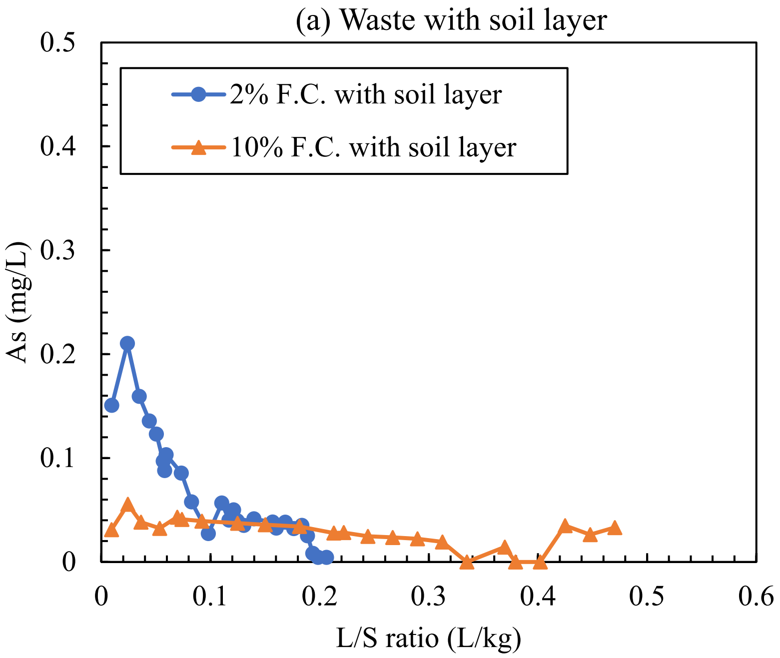


Figure 4.14 Change in As with increase in L/S ratio

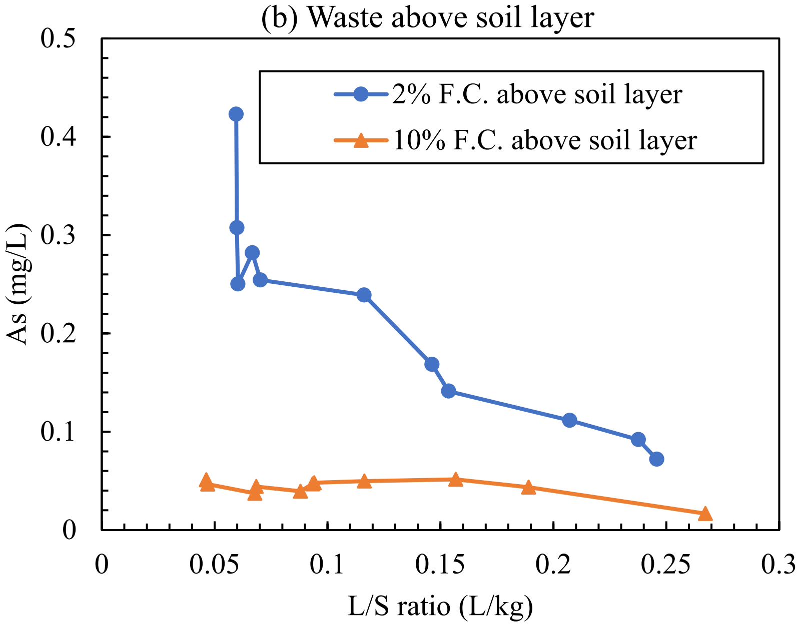


Figure 4.14 Change in As with increase in L/S ratio

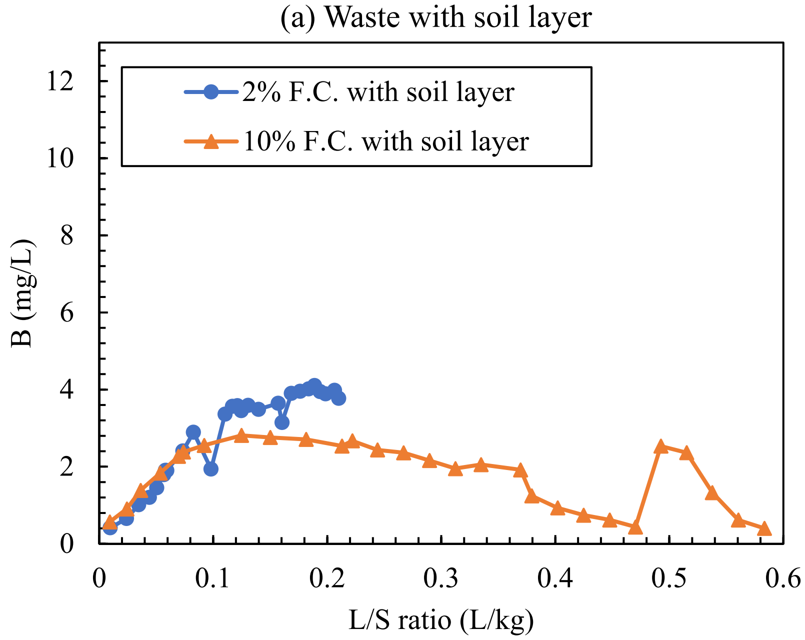


Figure 4.15 Change in boron with increase in L/S ratio

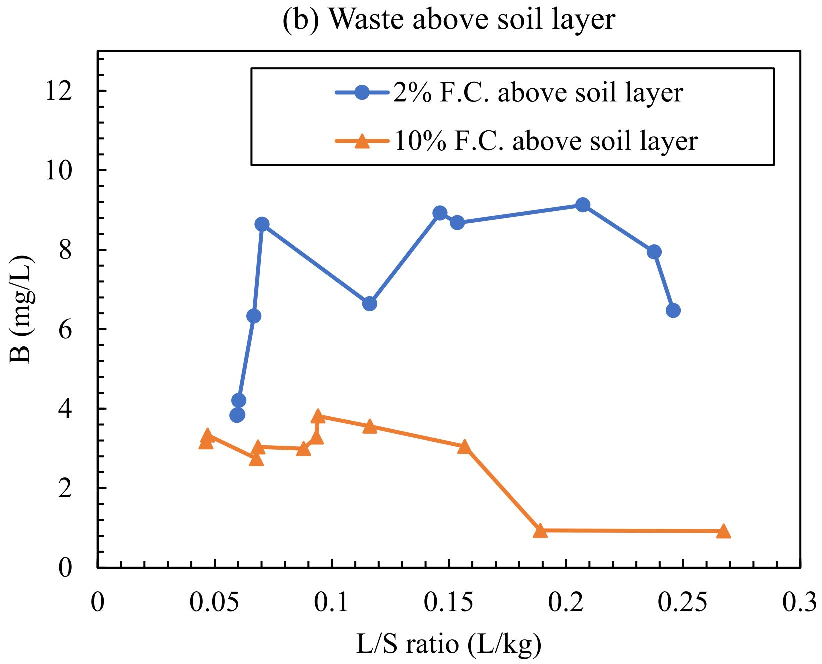
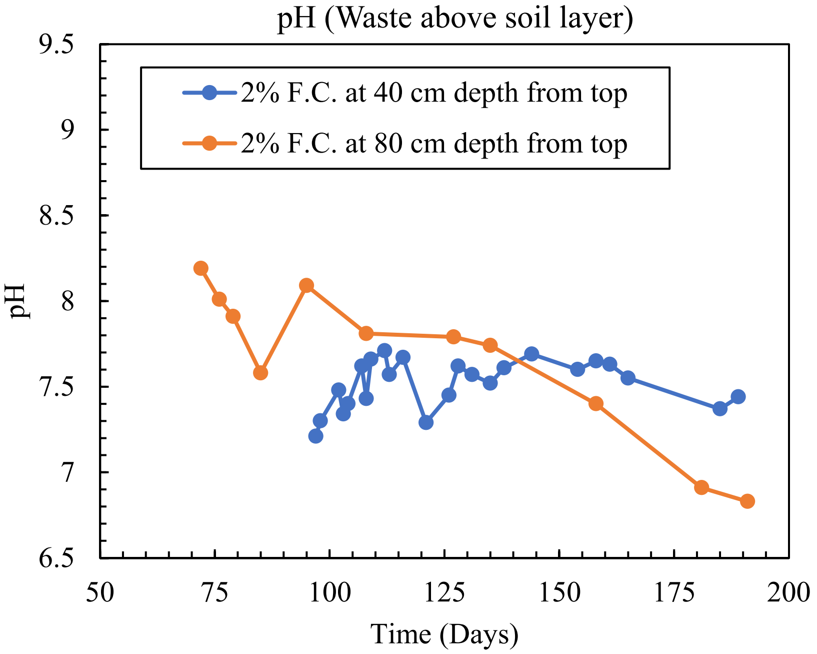


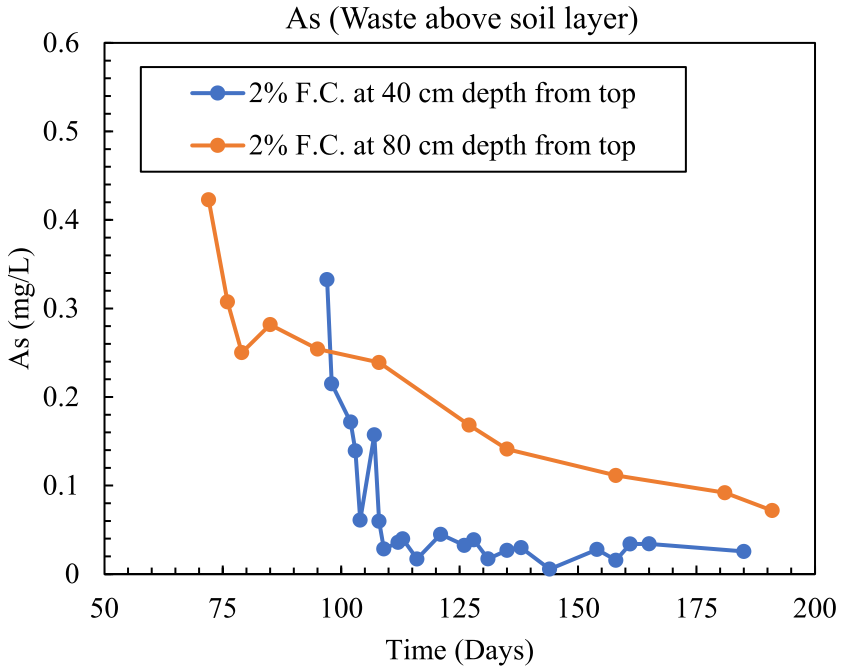
Figure 4.15 Change in boron with increase in L/S ratio

Leachate quality due to variation in depth of waste

The leachate quality for variation of depth of waste was also evaluated from the column test. For the column with 10% F.C., due to high drainage, the water was not stored for sufficient time at 40 cm from the top of the waste; therefore, leachate could not be collected at that point. Therefore, comparisons for different depths (40 cm and 80 cm from the top of waste) could not be carried out for column with 10% F.C. However, for column with 2% F.C., the comparison was possible. The leachate quality due to variation in depth of waste for column with 2% F.C. are shown in Figure 4.16. With increase in the depth of waste, pH values increased. For greater depth, with increase in time, the pH value decreased at a greater rate. The mixing of leachate with soil layer below the point of leachate collection may be the reason. Heavy metals also increased with increase in the depth of waste. For higher depth, the heavy metals decreased at a slower rate, but for lower depth the heavy metals decreased at a faster rate. It may be because with increase in time, the heavy metals were washed away from the lower depth (top part of the column) and it may be deposited or mixed with the waste at higher depth (bottom part of the column).



(a) pH for different depths of column with 2% F.C.



(b) As for different depths of column with 2% F.C.

Figure 4.16 Leachate quality due to variation in depth of waste

4.4 Laboratory batch leaching test

Batch tests can be conducted within a short time period of 6-24 hours, and therefore, they are considered as quick tests. In this research, the batch leaching test was conducted to have a quick idea about the physical properties and amount of heavy materials present in the leachate of the inert waste samples before using them in the laboratory column test.

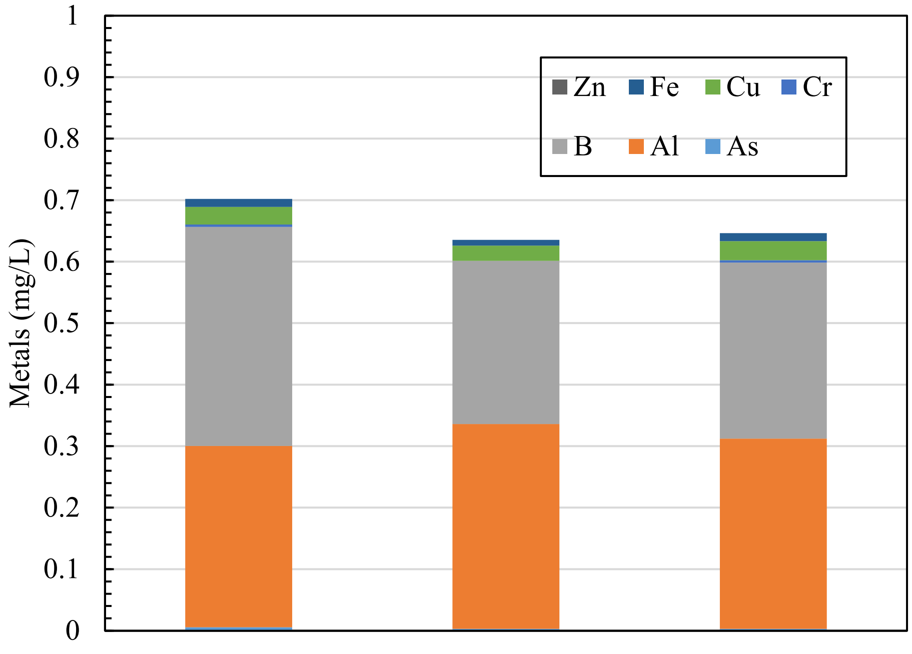
4.4.1 Methods and materials for laboratory batch leaching test

The procedure from JLT 13 (revised) was followed to conduct the batch leaching test. For batch leaching test, first, the inert waste materials collected from Chiba landfill were sieved through 5 cm × 5 cm openings. These sieved inert waste samples were of the same size used for the laboratory columns. The sieved materials were then mixed thoroughly. After that, 200 grams of waste samples were taken in 2000 ml plastic bottles and mixed with water of pH = 3, pH = 6 and pH = 9. The liquid to solid ratio (L/S) was 10. Similar samples were also made for the soil samples collected from the Chiba landfill. Twenty-five grams of soil samples with size less than 2 mm were taken in 250 ml plastic bottles and mixed with water of pH = 3, pH = 6 and pH = 9 at L/S ratio of 10. After mixing with water, the waste and soil were shaken continuously for 6 hours at 200 rpm. After shaking, the samples were collected and kept for settlement. After settlement, leachates were collected in tubes and centrifuged for 10 minutes in 3000 rpm. After that, the supernatant liquid was taken out and analyzed for pH, EC, Eh, and heavy metals. Figure 4.17 shows the batch leaching test during the shaking period. The batch leaching test was conducted on the inert waste materials before using them in the laboratory column test.

Figure 4.17 Laboratory batch leaching test

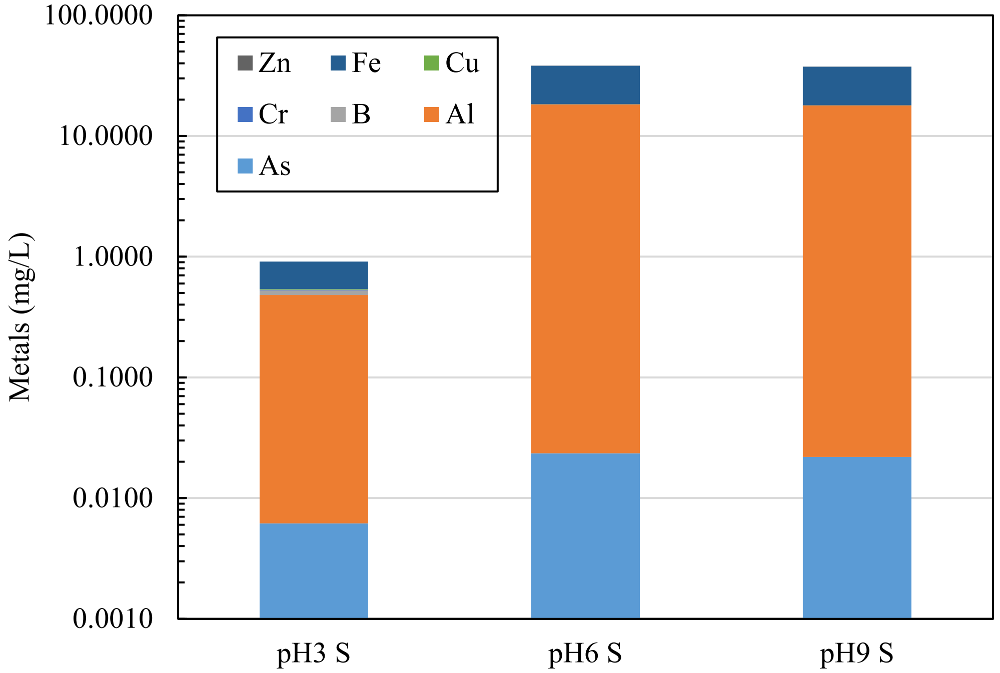
4.4.2 Results and discussion for laboratory batch leaching test

In the best leaching test, due to the continuous shaking, the inert waste was thoroughly mixed with the water. After analysis, the waste and soil both were classified as moderately reduced with Eh values of 302.2 mV and 350.47 mV respectively. Both waste and soil were highly alkaline in nature with pH values of 10.29 and 9.34, respectively. The alkaline nature of the waste is assumed to come from the CaO present in the construction and demolition waste. Figure 4.18 shows the heavy metals for different pH conditions. Metals such as Zn, Fe, Cu, Cr, B, Al, and As were measured using ICP-OES series 700 and Atomic Absorption Spectrophotometer, AAS (AA-6800). Al was found in a higher concentration for both inert waste and soil. Metals in soil leachate were higher than waste leachate. In the soil leachate, after Al, As and Fe were also found higher in concentration. The soil seemed to be naturally contaminated. Leaching behaviours under acidic rainfall were different for waste and soil. Further study is needed to explain this behaviour.



(a) Waste leachate for different pH

Figure 4.18 Metals in waste and soil leachate for different pH conditions



(b) Soil leachate for different pH

Figure 4.18 Metals in waste and soil leachate for different pH conditions

4.5 Conclusions for this chapter

Large scale lysimeter test

In lysimeter tests, drainage behavior of leachate was studied and possibility of presence of contaminants were checked. Change in parameters such as dissolved total organic carbon (TOC), total nitrogen (TN), Sulfate ion (SO_4^{2-}) with respect to the liquid-solid ratio (L/S) was observed for 5 sites of inert waste landfills. Sorption of toxic materials in leachate water was observed for soil layer under the waste or soil mixed with waste. In case of highly compacted waste, deterioration in quality of leachate was observed, but the values of most of the contaminants were found within standard limit. These observations were highly depended on the samples. It was assumed that heterogeneity in basic property (ex; size and shape) of inert wastes showed these varieties in the quality of leachate.

Laboratory column leaching test

Laboratory column leaching tests were conducted with columns having 2% and 10% fibrous content to know leaching characteristics of inert waste landfills due to variation in fibrous content. Drainage of water was higher for high fibrous content (10% F.C.). The water storage and EC were lower for the column with high fibrous content (10% F.C.) than that of low fibrous content (2% F.C.). From the column leaching test, it was confirmed that the higher fibrous content in the waste materials does not store leachate if they are smaller in size. The presence of organic matters was confirmed from the TOC test but the value was found to be within the standard limit. Moreover, the Total organic carbon, As and boron etc. were also lesser in case of high fibrous inert waste materials. With high fibrous content, the density becomes lower which makes the drainage higher and water contact time lesser. Soil layer installation seemed to be an effective solution for sorption of heavy metals etc. and buffering capacity. With increase in the depth of waste, pH values and heavy metals increased.

Laboratory batch leaching test

The batch leaching test was conducted to have a quick estimation of amount of heavy materials present in the leachate. The waste and soil both were classified as moderately reduced and highly alkaline in nature. The soil seemed to be naturally contaminated. Leaching behaviors under acidic rainfall were different for waste and soil. The results of the batch leaching test can also be used as an alternative for lysimeter and laboratory column test, but the results obtained may not be very precise as it is a quick leaching test.

Chapter 5

Slope stability

5.1 General remarks

In Japan, the fiber fractions present in inert wastes generally varies from 3 to 54% (Sarmah et al. 2020). Still, the design instructions followed by the inert waste landfills in Japan underestimate the tensile resistance offered by the fibrous content. Presently, the slope gradient of the inert waste in Japan is 1:2 which is same as the regulated slope of soil embankments or the municipal solid waste (MSW) landfill slopes. Due to tensile resistance offered by the fibrous content in the inert waste, there is a probability of making this slope gradient steeper than the existing one. Steeper slope gradient facilitates the use of the same landfill area for longer period of time, thus making it economical in regards to construction costs and future use. Recently many developing countries such as India, Vietnam etc. are also focusing on the proper disposal of construction and demolition wastes as these countries producing a huge amount of construction and demolition waste due to recent growth in country's infrastructures. Therefore, more rational and economical design methods are also needed for these developing countries. In this study, an approach to fulfill those design ambitions to get a steeper slope was followed with three approaches — in-situ investigation on strength parameters, centrifuge model test under seismic conditions, and dynamic analysis of landfills under normal earthquake (L1) or rare strong earthquake (L2) conditions. The overall structure of this study can be divided into five parts as shown in Figure 5.1. For part 1, field tests such as in-situ density, water content measurement, SPT test, PS logging, repose angle test and direct shear tests were carried out on inert waste landfill sites, from which physical parameters such as density, water content, N value etc. and strength parameters such as repose angel, internal friction angle, cohesion and shear wave velocity were obtained. In-situ density, water content, and shear wave velocity were used as input parameter for dynamic analysis. For part 2, laboratory direct shear test was conducted with two aims- firstly, for qualitative verification of the in-situ strength discussed in Part 1 with laboratory test and secondly, to determine the specification of centrifuge model landfill. Silica sand was used as the landfill material for centrifuge model test, where the behavior of landfill slope during earthquake was discussed. The centrifuge model test was discussed in part 3. For part 4, dynamic response analysis on behavior of landfill slope during earthquake was studied. For dynamic analysis, first qualitative verification of centrifuge test results was carried out and then parametric study was conducted considering some important factors of in-situ landfill slope. After completing part 1 to part 4, finally in part 5, some new proposals on current design method for landfill slope was indicated.

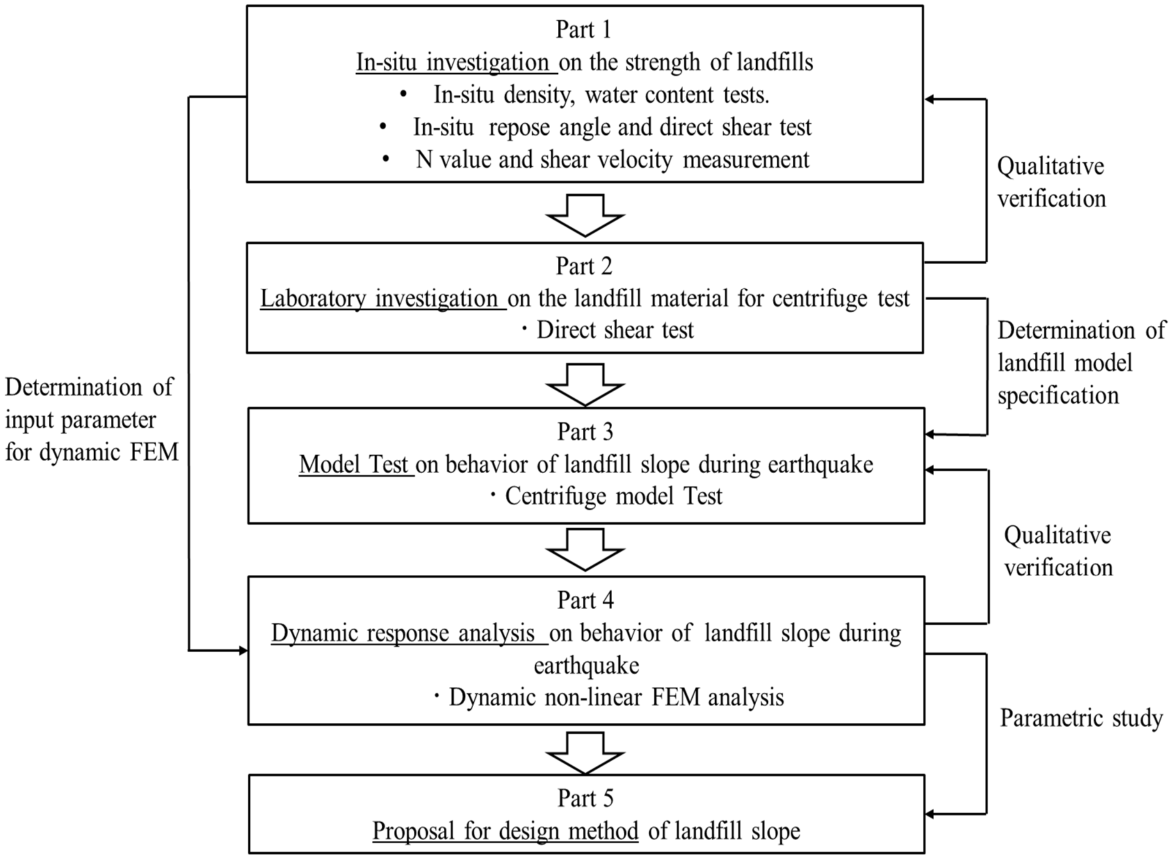


Figure 5.1 Flow chart for overall structure of this paper

5.2 In-situ tests (verification)

From the in-situ tests, basic physical parameters such as in-situ density, water content; strength parameters such as repose angle, internal friction angle; and shear velocity of the inert waste materials were obtained including the effect of fiber content and were later referred or used as the input parameters for dynamic analysis.

5.2.1 Methods and materials

In-situ investigation on density, water content, repose angle test, direct shear test, and shear wave velocity test were conducted at 14 locations of inert waste landfills in Japan to understand the physical and shear strength characteristics of inert waste with fibrous content, and to obtain the N value and shear wave velocity of the inert waste materials (at one site in Sendai). In-situ density test was conducted by water replacement method. Repose angle and internal friction angles are important for slope stability analysis as these are directly related to the shear resistance of soil. To calculate the slope stability, the angle of repose after avalanche was taken as the angle of repose, because Yamawaki et al. (2017) found that in case of flat grounds, angle of repose after avalanche is the maximum slope gradient at which the slope failure or crack does not occur. The slope angle before the collapse is called as critical angle of repose (α_c) and the slope angle after the avalanche is known as the angle of repose after avalanche (α_a) (Matsukura et al. 1989). The details of the repose angle test and direct shear test are described in Sarmah et al. (2020). Figure 5.2 shows measurement of repose angle and Figure 5.3 shows in-situ direct shear test conducted at inert waste landfill sites. The in-situ investigation density, water content, direct shear, repose angle test etc. confirmed some useful information about properties of waste material especially effect of fiber content which was already reported by Yamawaki and Sarmah et al. (2020). However, these investigations were conducted at the compacted surface of landfills. Therefore, to get the information about distribution of N value, water content and shear wave velocity with depth, additional field investigation of SPT test and PS logging (plate hammering) test in one landfill area in Sendai was executed. The obtained information was useful for evaluating the distribution of the waste properties with depth. It could also be used to determine the laboratory testing condition (like compaction degree of specimen) and input parameters for the dynamic analysis.

Figure 5.2 In-situ repose angle test

Figure 5.3 In-situ direct shear test

5.2.2 Results and discussion

From the past research of Yamawaki et al. (2017), and Sarmah et al. (2020), variations of physical and mechanical parameters with fibrous contents can be observed as shown in Table 5.1. Figure 5.4 shows the change in shear strength with increase in fibrous content obtained from in-situ direct shear test as a representative of Table 4.1. Results for other parameters are shown and discussed in detail in the previous work by our co-author Yamawaki et al. (2017), and Sarmah et al. (2020).

Table 5.1 Change in various parameters of inert waste with fibrous content from previous studies

Parameters	Fibrous content (Large size)	
	High	Low
Dry density	Decreases	Increases
Water content	Increases	Decreases
Cohesion c	Decreases	Increases
Internal friction angle φ	Increases	Decreases
Repose angle	Increases	Decreases
CASPOL impact value	Decreases	Increases
Poisson’s ratio	Decreases	Increases
Shear velocity	Decreases	Increases
Young’ modulus E	Decreases	Increases

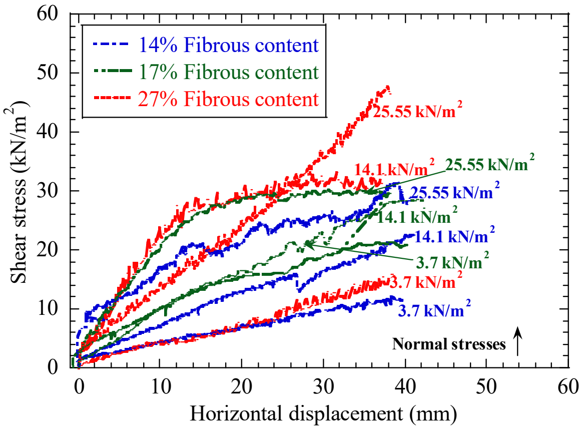


Figure 5.4 Shear stress vs horizontal displacement for in-situ direct shear test

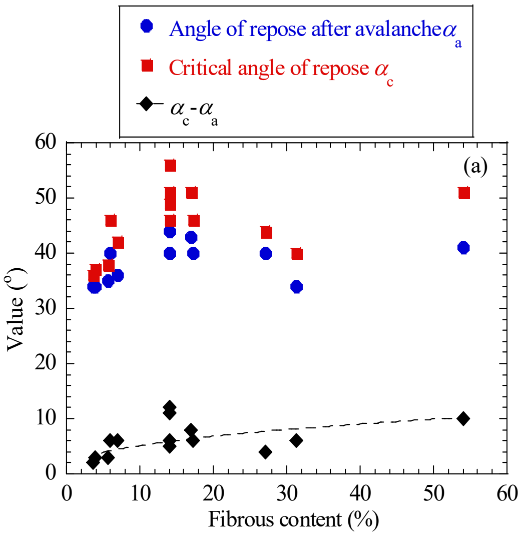


Figure 5.5 Repose angle vs fibrous content for inert waste landfills

The shear strength increased with increase in fibrous content under 30%. With high fibrous content, stress-deformation relation changed to strain-hardening and ductile shape. Figure 5.5 shows the change in repose angle with increase in fibrous content. Repose angle increased with increase in fibrous content under 15% due to tensile resistance of fibrous fractions.

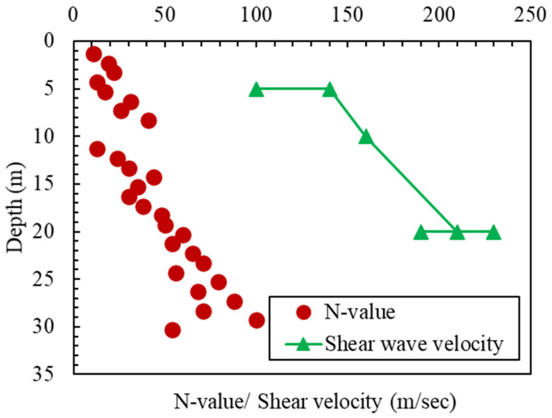


Figure 5.6. Change in N-value and shear wave velocity with depth

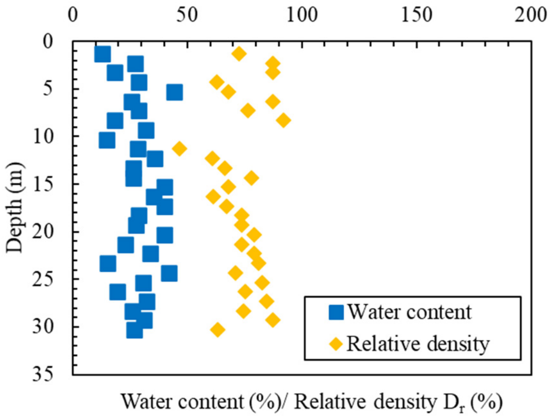


Figure 5.7. Change in water content and relative density with depth

Figure 5.6 shows the change in *N*-value and shear wave velocity with depth for an inert waste landfill site in Sendai and Figure 5.7 shows the change in water content and relative density D_r with depth for the same site. *N*-value increased with increase in depth. Water content changed from 15 to 40% and was not uniform. At depth 11-16 m, N-value was smaller and the water content was higher. Clay soil present in that area (confirmed from the core sample) was the reason for the small *N*-value and high-water content. V_s was also found partially smaller at this depth due to the same reason. Observation record of core sample confirmed the inert waste composition consisting of plastic, reinforced plastic, PVC, glass, glass fiber, cloth, vinyl, brick, and smelled a bit like garbage.

D_r of in-situ waste material was calculated by Meyerhof's equation as written below

$$D_r = 21 \text{ x } (N/(0.7 + \sigma_v/98))^{0.5} \ldots\ldots\ldots\ldots\ldots\ldots(5.1)$$

Where, $\sigma = \gamma$ x depth, γ =13.2 (average value obtained from field investigation). Calculated D_r value was almost between 65 to 90%. Therefore, the landfill was in medium to dense condition including deep area compressed by large overburden pressure. At depth 12-16 m, D_r value was partially smaller (70%) because of presence of clay content. The shear wave velocity (V_s) obtained from in-situ PS logging are compared with the plotting made by Zekkos et al. (2008).

Zekkos et al. divided the waste as rigid waste with large cohesion (*c*) and soft waste with small *c* value. Rigid waste was having plenty of sand, gravels etc. (100% < 20 mm) which facilitate its compaction thus increasing the dry density and *c* value. On the other hand, soft waste was consisting of lots of fibrous material (5% ~ 25% < 20 mm), which makes it difficult to compact them, thus decreasing the dry density and *c* value. In Zekkos et al. 2008, with increase in fibrous content (for soft waste) V_s decreased and with increase in sand and gravel (for rigid waste) V_s increased. The shear wave velocities (V_s) obtained from in-situ were near to the rigid waste and it showed the depth (overburden pressure) dependency as shown in Figure 5.8. The confirmed in-situ shear wave velocity V_s of waste material from Japanese inert waste landfill site was closer to the past research including the depth dependency and it also corresponded to N value distribution as mentioned above, therefore, this value was used for determination of input parameter for dynamic analysis.

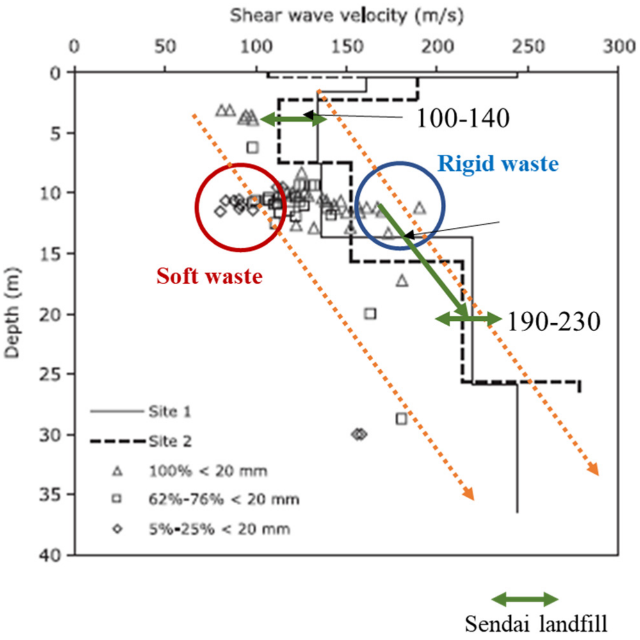


Figure 5.8. Shear wave velocity

5.3 Laboratory tests

Remarkable change in shear strength of silica sand due to fibers mixing was re-confirmed by laboratory constant volume and constant pressure direct shear test before using them in centrifuge model to verify the results shown in Figure 5.4 and Figure 5.5 and specification of landfill model in centrifuge test was also fixed. Centrifuge model test was conducted to understand the slope failure behavior and its physical mechanism mainly by checking the lateral earth pressure acting on the landfill embankments. Due to size restriction of the centrifuge model, difficulty in reproducing the grain size distribution of in-situ landfill material in detail, and to secure the reproducibility of each cases, uniform silica sand and artificial uniform fiber was used as simulated waste materials in the landfill models.

5.3.1 Methods and materials

Laboratory Direct shear test

Figure 5.9 shows the preparation of specimen for direct shear test. The shear box of the direct shear test apparatus was of 60 mm diameter and 20 mm height. In this test, fibrous content used were made artificially by cutting Nylon screen door into small pieces of size 1 cm. The mixing of silica sand and fiber were done by spreading the fibers in layers and pouring the silica sand from above to fill the voids. This way of specimen preparation required a total fibrous content of 3.6% (by the ratio of dry weight). Relative density of the specimen was made as 60% considering it as the real case scenerio of landfills. Field relative density D_r obtained in Sendai was 65-90%. Therefore, D_r in direct shear and centrifuge test was taken as 60% below this in-situ range to be in a safer side. There are two types of direct shear tests depending on the difference of volume change condition during shear, constant pressure and constant volume. In strong earthquake, landfill material usually sheared between these two volume change conditions and the actual shearing condition is unknown. Therefore, to have a better understanding about the influence of shearing condition, we tried both constant pressure and constant volume direct shear test. In the test, overburden pressure was taken as 60 kN/m^2, which was close to the overburden pressure in the middle depth of centrifuge model after 50g gravity as mentioned below in the description of the centrifuge model test method.

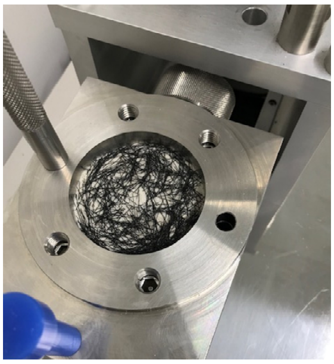


Figure 5.9 Preparation of specimen for direct shear test

Centrifuge test

The centrifuge test machine from Maeda Corporation with an effective radius of 3.5 m was used for this research. The centrifuge machine is shown in Figure 5.10 and the detailed diagram of the landfill model is shown in Figure 5.11. In the previous in-situ tests, the water level was not observed within the inert waste landfill layer and it is common for Japanese waste sites. In general, inert waste landfill material is assumed to have high permeability, therefore water level was not considered in this test. Dry silica sand was used as the waste material in centrifuge test. Considering a prototype of 5 m in one layer, the height of each landfill model was made of 10 cm and the slope gradient was taken as 1:1. Only two layers of landfills could be made with that size due to the size restriction of the test box and due to the same reason 2nd embankment is not perfect trapezoid. Four models of landfills were prepared among which two were of silica sand without fiber and the another two were reinforced with fiber. The four different cases i.e., case 1 to case 4 of the centrifuge test model and their respective parameters are shown in Table 5.2. For case 1, case 2 and case 4, the bottom layer embankment was at a distance of 2 cm (1 m in prototype) from the left wall of the test box and for case 3, the bottom layer embankment was fixed with the left side of test box. 1% F.C (fiber content) was taken for the reinforced models (case 2 and case 4) as the higher shear resistance due to increase in fibrous content was confirmed by the past triaxial test done by authors (Sarmah et al. 2020). In the direct shear test fibrous content was 3.6%, but the authors already confirmed the increase in shear strength of landfill material containing 1% fiber, so 1% fibrous content was chosen to be on the safer side. The author's aim was to mix the fiber material as much as possible while installing the specimen in the laboratory. The size of specimen, used material for landfill models, and fiber material's quality and size were quite different between triaxial and direct shear test. As a result, in triaxial test 1% and in direct shear test 3.6% were the maximum content in each experiment's specimen installation. In centrifuge test, specimen size was closer to triaxial test (diameter 100 mm and height 200 mm). Therefore, 1% fibrous content was taken considering two reasons- the size of specimen and to be on the safer side. The fibrous content used for laboratory test was much lower than the fibrous content obtained in in-situ investigation. The fibrous fractions present in the landfills are larger in size and sometimes they contain some metallic fiber etc. Moreover, due to the smaller specimen size, there was a difficulty in compaction of small sized inert waste with high fibrous content. Therefore, to maintain the density the inert waste, fibrous content used was lesser than the field value.

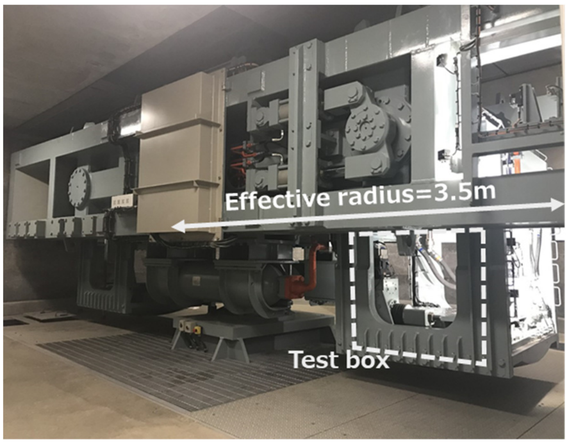


Figure 5.10 Centrifuge machine (Maeda Corporation)

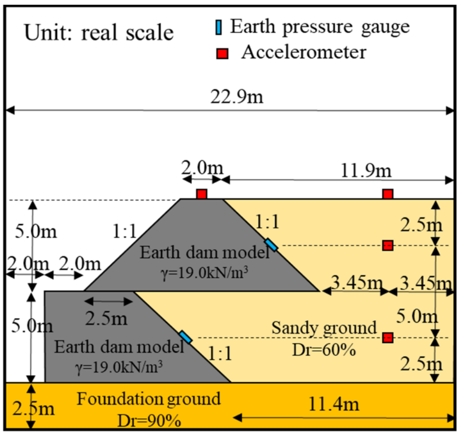


Figure 5.11 Model used for centrifuge test

Table 5.2 Parameters of four cases tested in centrifuge machine

Cases	Slope	Bottom layer embankment	Relative density	Fiber	Input acceleration
Case 1	1:1	Slidable	60% both layers of landfill	None	100gal-200gal-300gal-400gal
Case 2		Slidable		1%	
Case 3		Fixed		None	
Case 4		Slidable	90% for top layer of landfill	1%	

The fibrous content for centrifuge model was made of polypropylene with the size of L = 30 mm and D = 0.4 mm. The 30 mm size L in the model becomes 15 cm in prototype. 15 cm length for the real case scenario was selected due to the current legal regulation for maximum fiber length because of environmental reason of possibility of storage of water inside the fibrous fractions. Embankments were made of rigid acrylics, assuming it is made of cement improved soils. Its density was controlled close to common soil embankment (17 kN/m^3). Silica sand and fiber material were compacted together in many numbers of alternate layers with thickness, t = 10 mm each and 60% relative density above a foundation layer of 90% relative density for case 1, case 2 and case 3. The only exception was the case 4, where the top layer and foundation of the landfill was compacted with 90% relative density, and the bottom layer was compacted with 60% relative density. The reason for selecting this range of relative density is because of the relative density value obtained from SPT test in the field (65-90%) as mentioned earlier. The overburden pressure at the bottom of the top layer is 60 kPa, which is the same pressure used as constant pressure in direct shear test. Accelerometers were placed in the middle and top of the landfill layers and earth pressure gauges were connected at the center of embankment slopes inside the landfill. The models were then tested in a centrifuge machine under a gravity of 50 g (to install the in-situ overburden pressure) to check the slope failure behavior and lateral earth pressure acting on embankments due to increase in input acceleration of shaking table below the model. Input acceleration (sine wave of N =20, f =1Hz in prototype) was added step by step (100-200-300-400 gal). Accelerometers were placed at the horizontal direction only and earth pressure gauges were placed on the middle of the slopes of the acrylic embankment. Direct values obtained from the earth pressure gage value is shown for this paper, but true lateral earth pressure can be calculated by multiplying cos45° with it. Figure 5.12 shows the installing the fiber-sand mix layer for centrifuge model.

Figure 5.12 Installing fiber-sand mix layer for centrifuge model

5.3.2 Results and Discussion

Laboratory direct shear test

In Figure 5.13, shear stress with increase in horizontal displacement under constant volume and constant pressure direct shear test is shown for silica sand with fiber and without fiber. Change in shear stress and vertical displacement with increase in horizontal displacement under constant pressure condition are shown Figure 5.14. In case of silica sand without fiber, the shear stress increased with increase in horizontal displacement and then gradually saturated or decreased slightly after showing a peak value. On the other hand, shear stress continued to increase with increase in horizontal displacement without showing clear peak value for the case of silica sand with fiber. An increase in a fibrous content changed the material behavior from "brittle to ductile" and "strain-softening to strain-hardening". This result was similar to the past tests on strength characteristics of waste material in Japan (Miyamoto et al. 2015) and the past triaxial study conducted by the authors with inert waste collected from landfill sites (Sarmah et al. 2020). According to these studies, the change in strength of waste material was depended on several factors such as differences in shear test apparatus, fibrous content, orientation of fibrous material in the specimen, compaction degree of specimen etc. However, experiments were conducted only under drained or constant pressure shear condition, constant volume test was not executed using waste material. This direct shear test considered two factors for shear strength, fiber content and volume change condition.

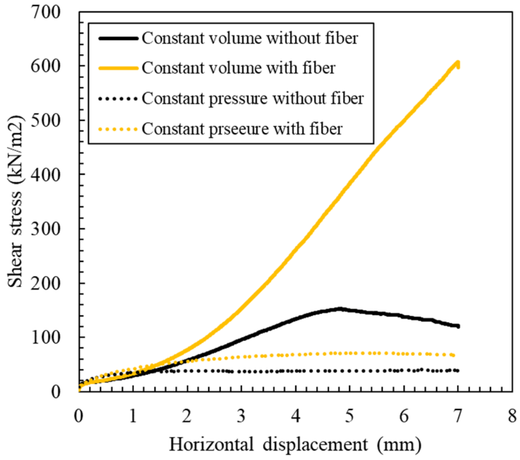


Figure 5.13 Shear stress with increase in horizontal displacement for constant pressure or constant volume

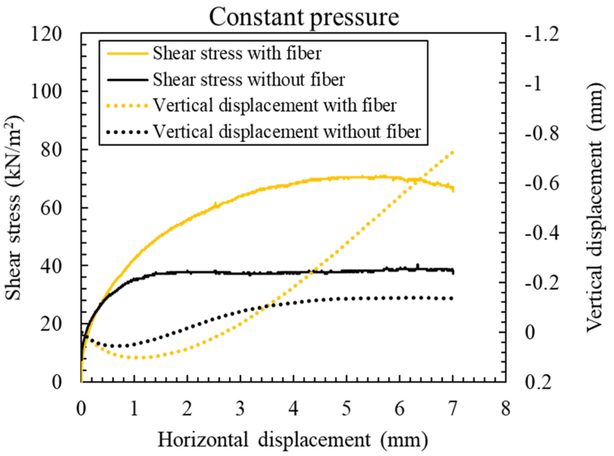


Figure 5.14 Shear stress/ vertical displacement vs horizontal displacement under constant pressure

Figure 5.13 demonstrated that under constant volume condition, waste material with higher fibrous content shows significant increase in strength with increase in horizontal displacement. According to Miyamoto et al. (2015) under constant pressure direct shear test, waste materials with high fibrous content showed clear and significant 'volume expansion' with increase of horizontal displacement. The expansion was dependent on the shrinkage quality of the fibrous materials. This phenomenon (including strain-hardening) was similar to the direct shear test results obtained in this research as shown in Figure 5.4 and can be explained only for a combination of soil and fibrous material. As under constant pressure direct shear tests, with high fibrous content waste material showed volume expansion, therefore, under constant volume direct shear tests, significant increase in strength with increase in horizontal displacement was expected with the synergy of increase in overburden pressure during constant volume shear and tensile resistance offered by the fibrous content. Stress paths in constant pressure and constant volume direct shear test with and without fiber are shown in Figure 5.15. The shear strength parameter internal friction angle φ was calculated using these data and it was observed that for silica sand with fiber (3.6% F.C.) showed a 6° increase in internal friction angle without fiber. This increased value was closer to the average increases value of repose angle obtained in the in-situ test as shown in Figure 5.5. The tensile resistance offered by the fibrous content increased the shear strength of the silica sand significantly. Inert wastes which usually contain fibrous fractions and construction or demolition waste etc., exhibit high shear strength than general embankments with only soil fraction. These characteristics of fibrous fractions is similar to the effect of artificial geotextile. From the results of the direct shear test, the increase in shear strength of the silica sand due to fiber mixing was confirmed. Therefore, the silica sand with fiber was determined to use as the waste material of the landfill models in the next centrifuge test.

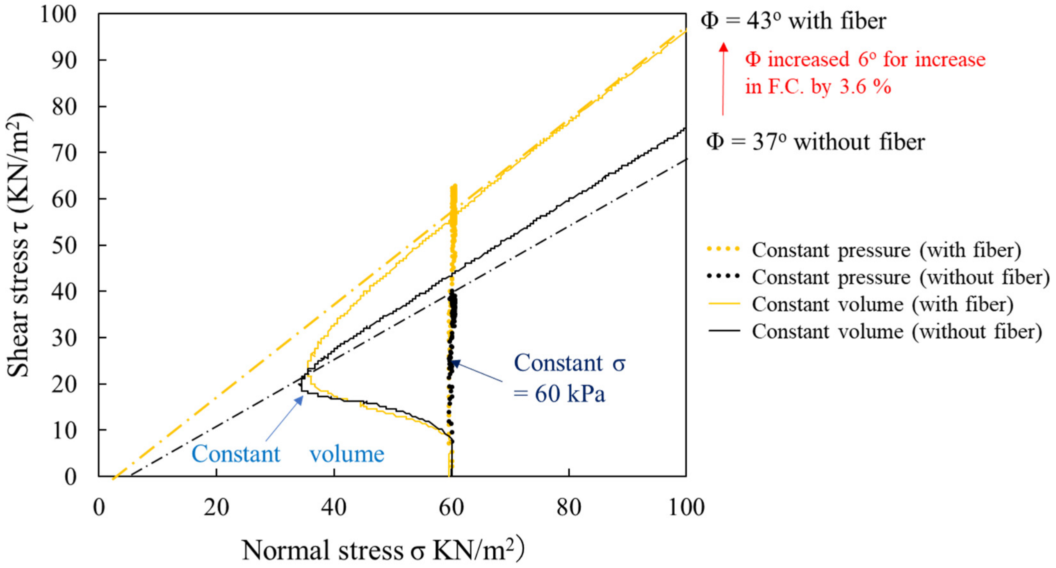
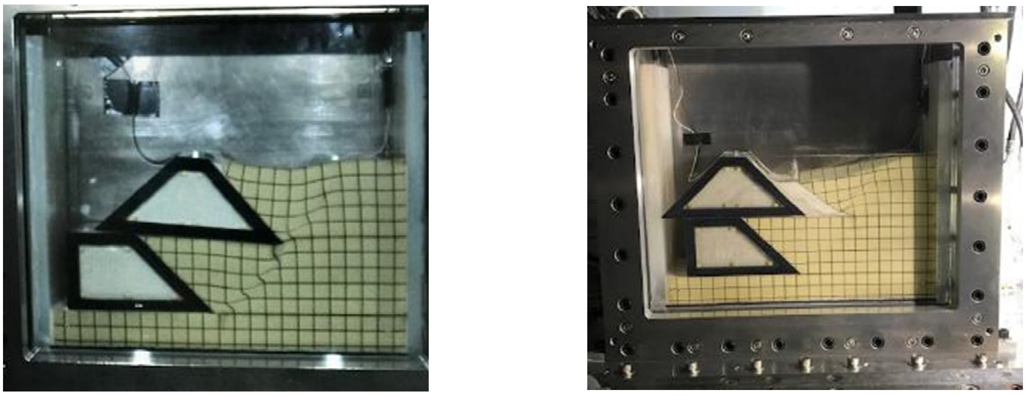


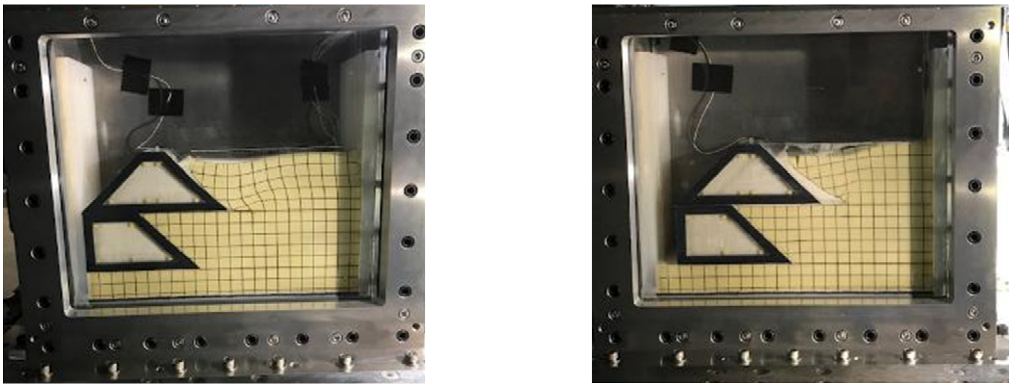
Figure 5.15 Shear path for silica sand with and without fiber

Centrifuge test

The slope failure behaviors of 4 different cases after completion of the centrifuge test (400-gal shaking) is shown in Figure 5.16. For case 1 (without fiber), successive linear slip line with clear shear band was observed including both top and bottom layer. The top layer embankment rotated in clockwise while sinking. Complete slide of upper and lower embankment occurred due to absence of tensile resistance of the fibers for case 1. Although, the bottom layer had the overburden pressure by the weight of top layer, it was considered not enough to overcome the shear failure in case without fiber. If there would be more numbers of layers, complete slide might have occurred including all the embankments making a total and large-scale slope failure. Therefore, repairing of the landfill after failure would not be possible or will require significant efforts. In case 2 (with fiber), the top embankment slides horizontally showing a massive deformation, but little deformation was observed in the bottom layer of landfill. Overburden pressure in bottom layer was larger than the top layer so, it was more resistant together with the tensile resistance effect of fibers. On the other hand, the top layer had less overburden pressure, and after a certain acceleration, the tensile resistance from the fibers in the top layer could not resist the shear anymore, thus deformation occurred at a greater rate and the top embankment slide.



(a) Case 1 (b) Case 2



(c) Case 3 (d) Case 4

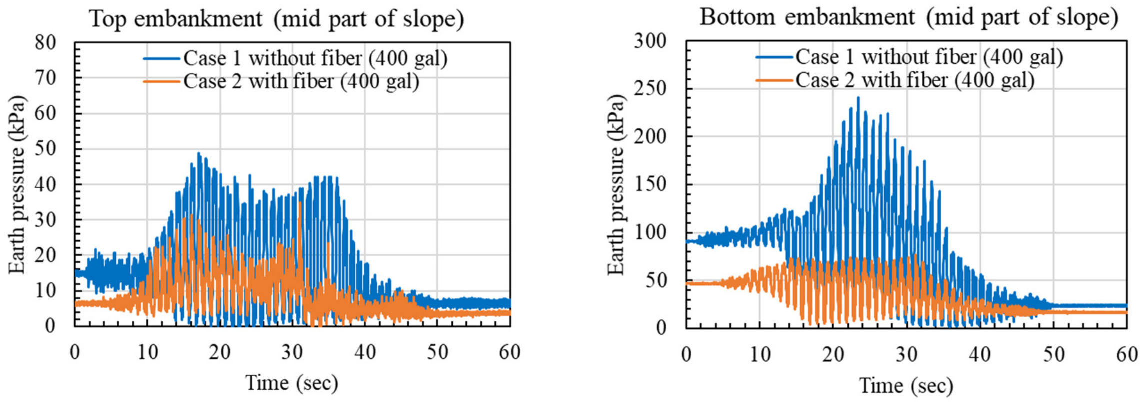
Figure 5.16 Comparison of slope deformation of each case after 400-gal vibration

This phenomenon in top layer in case 2 should be discussed later in detail indicating some observational data including before 400-gal shaking. In case 2, repairment of landfill maybe possible because the damage was limited to only the upper layer. If embankment had more than 3 layers, in the case with fibers, lower embankments would be more resistant than 2nd, so damage would be limited, but in the case without fiber (case 1), complete inevitable slide would have occurred including 1st to last embankment. For case 3 (without fiber and left side of bottom embankment fixed), local slip and subsidence was observed for the top layer of the landfill. Since the bottom layer of case 3 is fixed with the left wall, no deformation was observed for the bottom layer and total collapse of whole slope was not initiated. This result shows that slope stability of landfills is related simply to deformation restriction condition of embankment. It should be noted that deformations of the bottom embankment in case 2 (with fiber) and case 3 (without fiber but fixed) were almost the same. It means embankment and back landfills with fiber behaves like retaining wall with fully reinforced backfilling. For case 4 (with fiber, top layer more compacted to $D_r = 90\%$) similar trend as case 2 was observed, but the sliding of the top layer was lesser than case 2. It shows useful warning that after strong earthquake, some damage should be expected in the surface layer and it is difficult to avoid it only by densification using compaction machine. For countermeasures of the embankment slide, artificial geotextile in the top layer can be used, which helps in increasing frictional resistance within the landfill. Another countermeasure is increasing the friction between top and second embankment or increasing deformation restriction of the embankment. In centrifuge test, touch surface between top and 2nd embankment was very slippery, but in the field execution, we can increase the roughness of boundary by ‘raking’ which means digging several ditches on the surface of 2nd embankment by construction machine and constructing the top embankment on it.

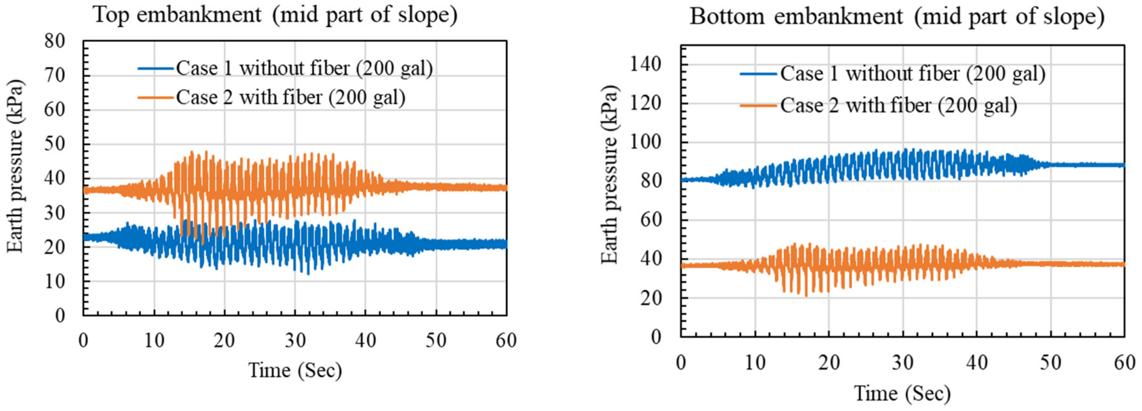
The slope failure behavior of the models can be better understood from the earth pressure acting at the midpoint of the embankment slopes and acceleration intensities measured at different points of the landfills and embankments. Figure 5.17 shows the earth pressures and acceleration comparisons for case 1 and case 2. The experiment model conditions were same for both of these two cases, except one was without fiber (case 1) and the other with fiber (case 2). The value of the static earth pressure in the bottom layer, before vibration (50 g centrifugal field) was smaller for sand layer with fiber than without fiber. This result coincides with result shown by the previous researcher in Figure 2.8. However, for top layer, the static earth pressure was found higher for sand layer with fiber and its reason is unknown. For the earth pressure without fiber condition, passive earth pressure situation was observed with increase in acceleration

(400-gal), which finally decreased to active earth pressure in both top and bottom embankments as shown in Figure 5.17 (a) and (b). With fiber, the earth pressure was lower than without fiber for both embankments, but the top embankment slide at a greater rate. It can be explained by the results obtained in the 200-gal and 300-gal shaking before 400-gal. For 200-gal case (considered to be L1 motion) as shown in Figure 5.17 (b) and (c), no slide or active failure occurred in both embankments for with and without fiber case. In case of 300-gal (close to L2 motion), for bottom embankment (with and without fiber) and top embankment (without fiber), no slide phenomena (passive to active) occurred and earth pressure almost returned to its initial value. However, in the top embankment and sand layer with fiber under 300-gal acceleration, passive to active condition was observed in the earth pressure, which made some slide in the embankment. For 200-gal acceleration, the initial earth pressure on top embankment was larger for case 2 with fiber which might be one reason of the embankment sliding. It is because in case with fiber, stiffness of bottom layer was larger than without fiber because of the tensile strength of fiber. Rigid bottom layer (with fiber) transferred more acceleration than soft bottom layer (without fiber) which is clear from the difference of acceleration figures for 300-gal. After 300-gal shaking, stiffness of top layer (with fiber) was almost lost because of the active failure; therefore, in the next 400-gal shaking, top embankment had no resistance to additional hard shaking thus slided significantly. If input motion is 300-gal, intensity of acceleration causes the slide of the top embankment (with fiber), but in that case, slide amount is not so large and its repairment is easy. However, it is certain that if we apply 300 to 400-gal acceleration for a continuous long term then condition like Figure 5.16 (b) is feasible. Therefore, preparation of some quick remedy treatment only for top embankment is considered to be necessary.

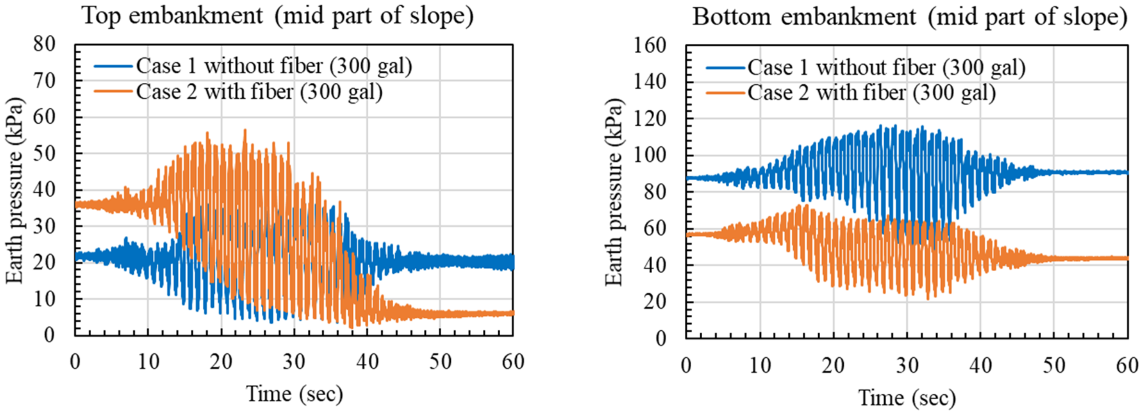
Figure 5.18 shows the earth pressure at bottom embankment under 200-gal and 400-gal shaking for case 3, where the bottom embankment was fixed to the wall. In this case, for 100−200-gal, only passive pressure increment was occurred and earth pressure at rest increased after shaking. After earth pressure at rest reached its upper values under 300-gal to 400-gal, the earth pressure returned back to almost initial value after adding dynamic earth pressure increment. This result shows that deformation restriction condition of embankment is deeply related to earth pressure acting on the embankment during shaking and sliding of embankment demonstrating that slope failure. It means slope stability of landfills is similar to that of design concept of retaining wall. It is also indicated that attention must be paid to increase the resistance against sliding of embankment in the field execution (For example, adopting the material with high stiffness and strength like cement improved soil for embankment is useful).



(a) Earth pressure at 400-gal (b) Earth pressure at 400-gal

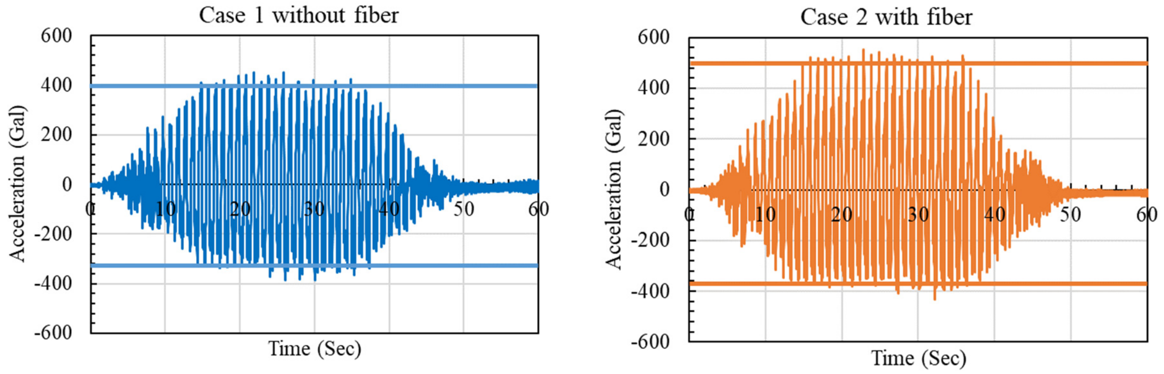


(c) Earth pressure at 200-gal (d) Earth pressure at 200-gal



(e) Earth pressure at 300-gal (f) Earth pressure at 300-gal

Figure 5.17. Earth pressures and acceleration comparisons for case 1 and case 2



(g) Acceleration at 300-gal

(h) Acceleration at 300-gal

Figure 5.17. Earth pressures and acceleration comparisons for case 1 and case 2

After observing the significant slide in top embankment in case 2 after 400-gal shaking, only the top layer and embankment was removed and re-constructed with fiber and compacting again to 90% relative density (bottom layer and embankment was not changed). Case 4 was conducted continuously after remedy of the top layer. Therefore, the bottom layer with fiber experienced twice shaking history. However, as shown in Figure 5.16 (d), this layer resisted this additional harsh shaking perfectly. It means synergy in landfills with enough fibrous content and overburden pressure have extremely high resistance potential(resiliency) to strong earthquakes.

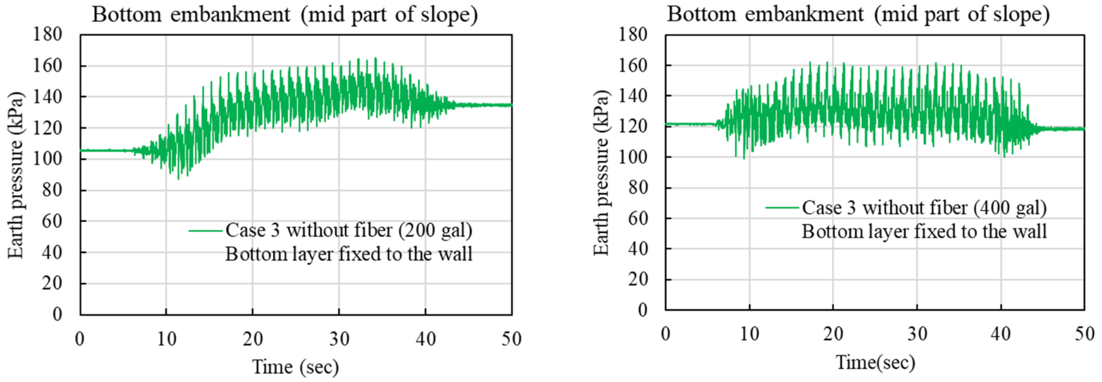


Figure 5.18 Earth pressure at the bottom embankment for case 3 in 200-gal and 400-gal

Figure 5.19 shows the earth pressure variation on top embankment of case 2 and case 4. Initial and dynamic earth pressure on the top embankment was found lesser than case 2 due to increase in stiffness of the top layer. Although there was some effect of densification of 1st layer, earth pressure finally changed to active condition and failure of the top layer could not be resisted in 300-gal. Therefore, another countermeasure should be considered for the top surface layer.

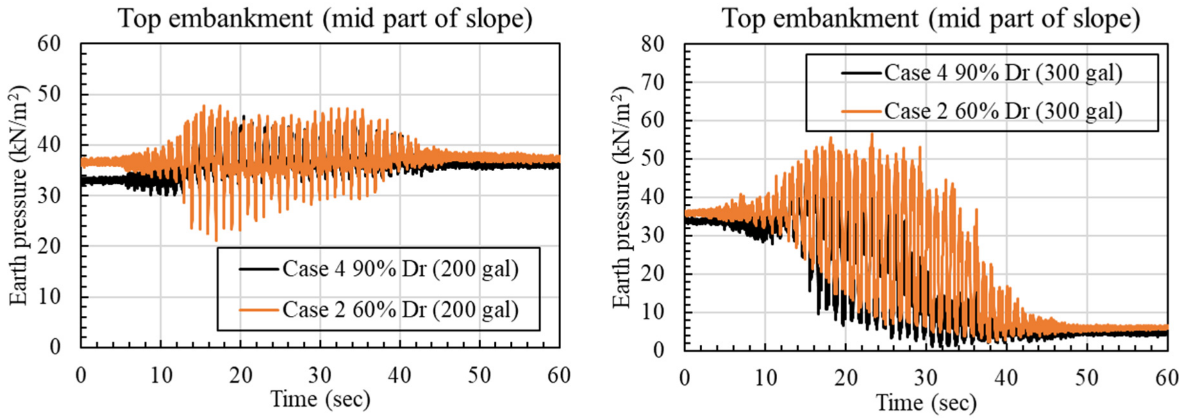


Figure 5.19 Earth pressure variation on top embankment of case 2 and case 4

5.4 Dynamic analysis

Dynamic analysis was conducted to fulfill two main purposes. Firstly, to understand the slope failure behavior under strong earthquake and to verify the slope failure mechanism obtained in the centrifuge test results with and without fiber (case1 and case2) qualitatively. Secondly, after verification, parametric study (sensitivity analysis) was conducted using some important factors of in-situ landfill slope, considering the difference of waste material with and without fiber to provide some useful suggestions for the current design method for inert waste landfills. Modified Ramberg-Osgood model was used for the non-linear analysis and incremental embankment analysis was executed using nonlinear elastic model in landfill element.

5.4.1 Analytical method

The governing equation (5.2) of motion for forced vibration due to an external force by earthquake shown below was solved at time interval Δt using Newmark- β (direct integration) method.

$$M\ddot{u} + C\dot{u} + Ku = -MI\ddot{u}_e \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.2)$$

Where u = displacement, M = mass of the system, C = damping coefficient, K = stiffness, $I = X\beta$, β is a parameter with range of $0 \leq \beta \geq 1/2$, and X = mode matrix.

In this equation, stiffness matrix K was calculated according to the constitutive equation by Hysteresis type Ramberg-Osgood model as shown in equation (5.3) below

$$\frac{\gamma}{\gamma_y} = \frac{\tau}{G_{max}\gamma_y}\left(1 + \alpha\left|\frac{\tau}{G_{max}\gamma_y}\right|^{r-1}\right)$$

…………………………(5.3)

Where, γ = shear strain, τ = shear stress, γ_y = reference shear strain, G_{max} = small strain shear modulus, material constant $\alpha \geq 0$, and $r \geq 1$.

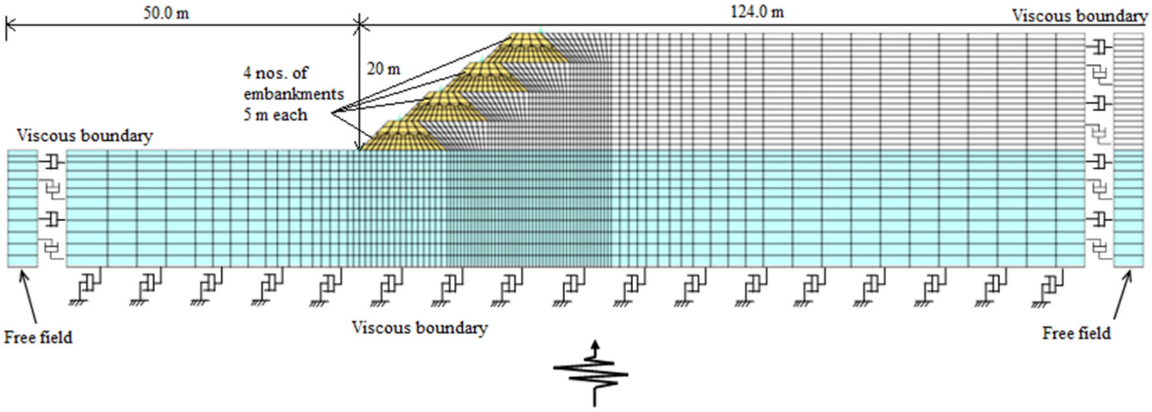


Figure 5.20 FEM model used for this study

Figure 5.20 shows the FEM model generated. Four numbers of embankments and landfill layers with height of 5 m for each layer were created on the rigid foundation of 20 m depth (blue area). Distance from the toe of bottom layer embankment to the left boundary was 50 m and to the right boundary, it was wider with a length of 124 m.

Before starting dynamic analysis, incremental embankment analysis was executed using nonlinear elastic model in landfill element. Embankments and landfill element were added from bottom to surface in turn to determine the initial stress before shaking and corresponding dynamic properties G_o, $G/G_o \sim \gamma$, $h \sim \gamma$ etc., which depend on the initial stress. Joint element was placed between embankment and back landfills because the failure mechanism of slope was observed as active failure by centrifuge test and this phenomenon occurs due to separation and slide between embankment and backfill. Viscous boundaries were placed at the left, right and bottom of the model and free field was combined with left and right viscous boundary (energy transmitting boundary).

The seismic wave recorded in Kobe (Great Hanshin Earthquake (1995)) was adopted as input motion for this analysis as shown in Figure 5.21. It was used directly as a rare strong earthquake

(L2), and, frequent medium earthquake (L1) was assumed just by reducing the acceleration value to half of L2 motion for convenience.

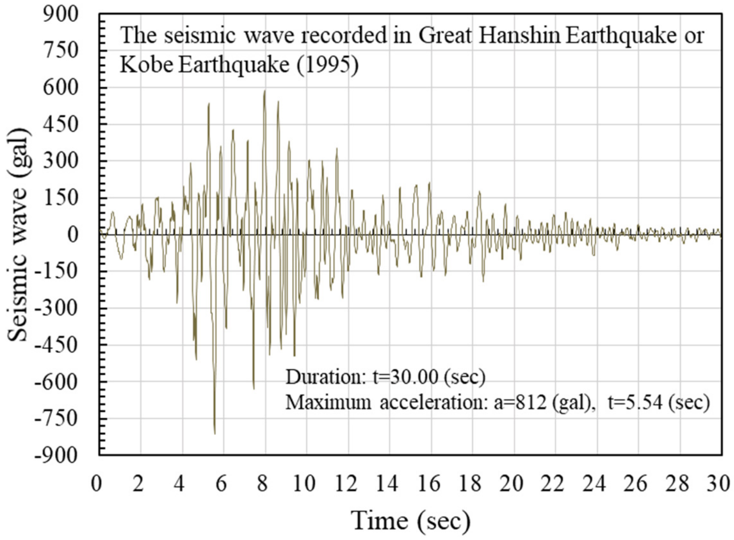


Figure 5.21 Input motion used for dynamic analysis

Analytical method used in this research is the common and conventional one, so that it can be easily used by the practical engineers in their actual design of landfill slope. On the other hand, this method has several limitations in expressing the actual seismic phenomena of slope as mentioned above.

5.4.2 Analytical case

For parametric study, four representative and important factors of in-situ actual landfill slope were selected as below.

1. Material characteristics of landfills dependent on the fibrous content present in the waste material. Soft waste material means waste with high fibrous content, indicating low density and low stiffness. Rigid waste material means the opposite. Their concrete values are shown in Table 5.4.
2. Material characteristics of embankment were of two representative types. Soft embankment corresponded to clayey soil and rigid embankment corresponded to cement improved soil. Those were considered to be minimum and maximum stiffness of embankment currently used for inert waste landfills in Japan.
3. Slope gradient was of three types: 1:1 (steep) ,1:1.5 (moderate), and 1:2 (conservative).

4. Input motion used were of L1 and L2 as mentioned before.

First, comparison between two cases of rigid embankment with slope gradient 1:1 and landfills with and without fiber were tried in L1 and L2 motion to verify the centrifuge test results qualitatively. Next, total 24 parametric studies indicating in Table 5.3 were executed to check the sensitivity of selected factors on slope stability.

Table 5.3 Cases for dynamic analysis

		Waste layer	
		With fiber (soft)	Without fiber (rigid)
Embankment	Cement improved soil (rigid)	1:1, 1:1.5, and 1:2	1:1, 1:1.5, and 1:2
	Clayey soil (soft)	1:1, 1:1.5, and 1:2	1:1, 1:1.5, and 1:2

5.4.3 Determination of input parameters

Several static and dynamic input parameters were determined for typical waste material and embankment in landfill slope shown in Table 4.3. Main parameters used for analysis were – (1) wet density γ_t, (2) Young modulus and Poisson's ratio for static analysis, (3) Dynamic deformation characteristics G_o, $G/G_o \sim \gamma$, $h \sim \gamma$ used for Hysteresis type Ramberg-Osgood model, and (4) Shear strength parameters c and φ used in joint elements.

Determination procedure of input parameter for waste material are described below.

The parameters were obtained mainly from several in-situ field tests mentioned before in this research and past research for dynamic properties of waste material by Zekkos.te.al (2008).

Dry density and water content of landfills and embankment

In Table 5.1, the effect of fibrous fractions on density of inert waste was already shown. Figure 5.22 shows the data of dry density and water content obtained from in-situ water replacement method. For dynamic analysis, approximate values of upper and lower dry densities of the inert waste were used and average water content 25% in Japan was used in both cases.

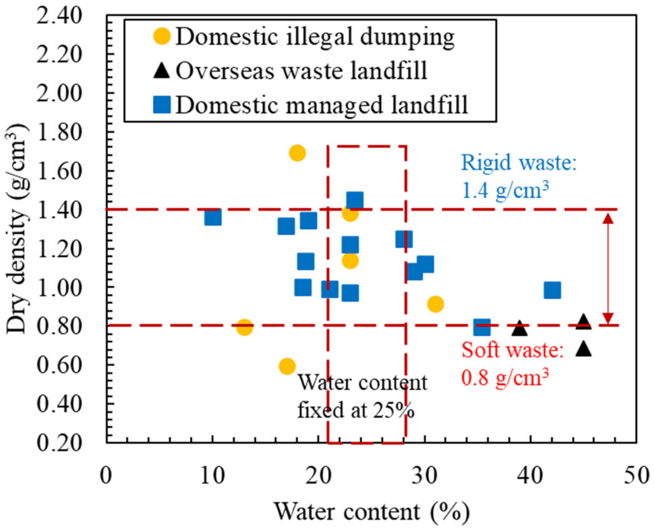


Figure 5.22 Relationship between dry density and water content for different types of landfills

Young modulus and Poisson's ratio used in static analysis

Young's modulus E was obtained from the in-situ Plate Loading Test (PLT). Figure 5.23 shows the relationship between the stiffness of compacted landfill ground K_{30} gained by PLT and impact value by CASPOL. Corresponding to the selected maximum and minimum values of dry densities from Figure 5.22, stiffness of compacted landfill ground K_{30} for soft waste and rigid waste were determined.

K_{30} by PLT was converted to Young's modulus E by elastic body theory by Boussinesq approximation (5.4)

$$E = 0.267 \times K_{30} \quad \text{...(5.4)}$$

This K_{30} value was obtained on site at the compacted surface of landfill ground, but it is considered to be increased with increase of overburden pressure referring the result of in-situ SPT test shown in Figure 5.6. Therefore, E was modelled as overburden pressure dependent nonlinear elastic body (Zekkos et al. 2008). Coefficient factor n for overburden pressure was same for both E and G_0 as mentioned below. Young's modulus E of the embankment was determined referring the assumed N value (N = 4 in clay embankment) and unconfined compressive strength q_u (150 kN/m^2 in cement improved soil).

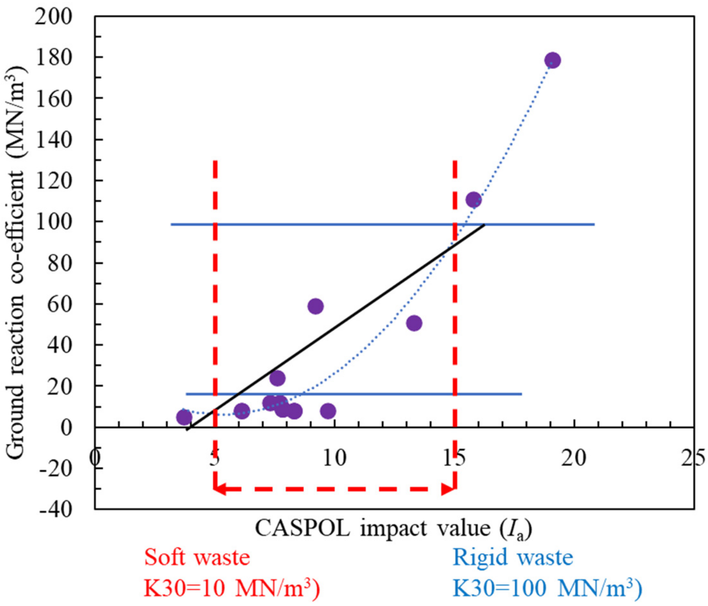


Figure 5.23 K30 vs CASPOL Impact value

Poisson's ratio ν of landfill with and without fiber was back calculated from the initial coefficient of earth pressure at rest K_o obtained by centrifuge model test using the equation of elastic body (5.5) as given below

$$\nu = \mathbf{K_o} / (1+ \mathbf{K_o}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.5)$$

The Poisson's ratio (ν) was smaller for soft waste and it coincided with the Poisson's ratio calculated by Yamawaki et al. (2013). Poisson's ratio ν was assumed to be same in static and dynamic condition.

Dynamic deformation characteristics G_o, $G/G_o \sim \gamma$, $h \sim \gamma$ used for Hysteresis type Ramberg-Osgood model

G_o was determined from before mentioned V_s value indicated by Zekkos et al. (2008) (which is close to the in-situ V_s value measured in our research) and dynamic properties G_o, $G/G_o \sim \gamma$, $h \sim \gamma$ etc. were determined by comparing the embankment curve with the curve drawn in Zekkos et al. (2008) as shown in Figure 5.24.

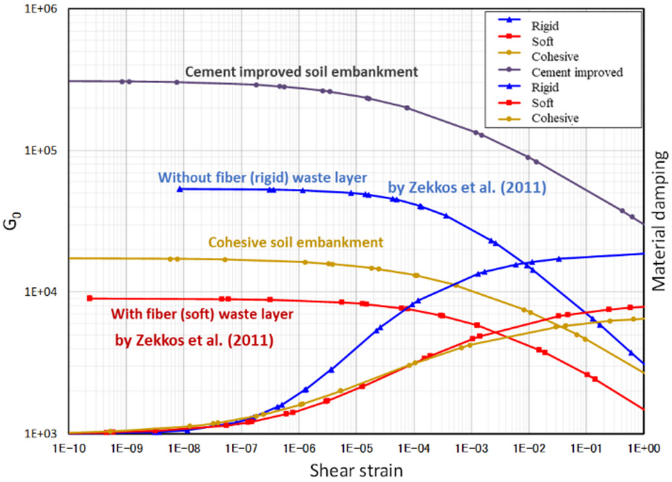


Figure 5.24. G_o/ material damping vs shear strain for waste layer and embankments

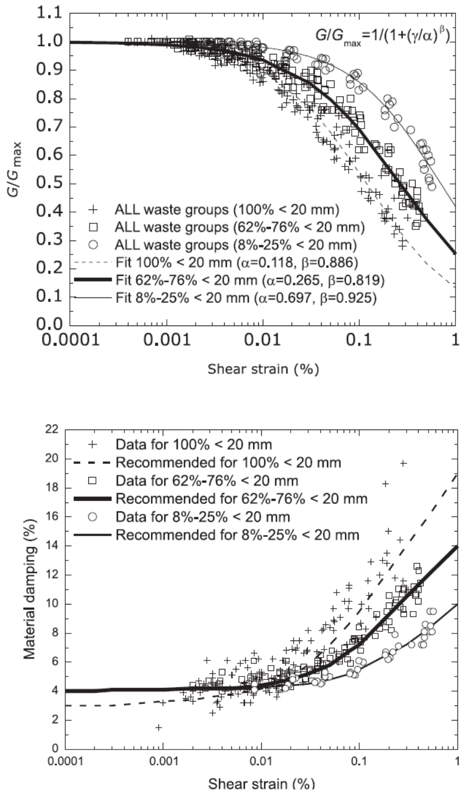


Figure 5.25 (G/G_{max})/ material damping vs shear strain for waste (Zekkos et al. 2008)

Determination of dynamic deformation properties of waste materials was practically difficult, but Zekkos et al. (2008) reported this information in detail, therefore, their outcome was referred in this research. $G/G_o \sim \gamma$, $h \sim \gamma$ curve for waste material by Zekkos et al. (2008) is shown in Figure 5.25. According to Zekkos et al. (2008), with increase in fibrous content of size > 20 mm, the small strain shear modulus G_{max} decreased and the normalized shear modulus curve shifts to the right as reference strain γ_r increases. Material damping h decreased with increase in fibrous content and it showed elastic behavior similar to the direct shear test result with linear stress-displacement relationship already shown in Figure 5.4.

Shear strength parameters c and φ used in joint element

Input parameter for joint element was set as it cannot resist separation and the shear resistance between embankment and back landfill, which depends on cohesion (c) and internal friction angle (φ) of waste material. Corresponding to the maximum and minimum value of selected dry density and change of repose angle with increase in fraction of fibrous material, c and φ of joint element was determined. In joint element, stiffness of normal spring was set large enough in compression direction so that the joint element never overlaps and small enough in tensile direction so that the joint element can easily separate if normal stress becomes zero. The input parameters from field tests used for dynamic analysis are shown in Table 5.4.

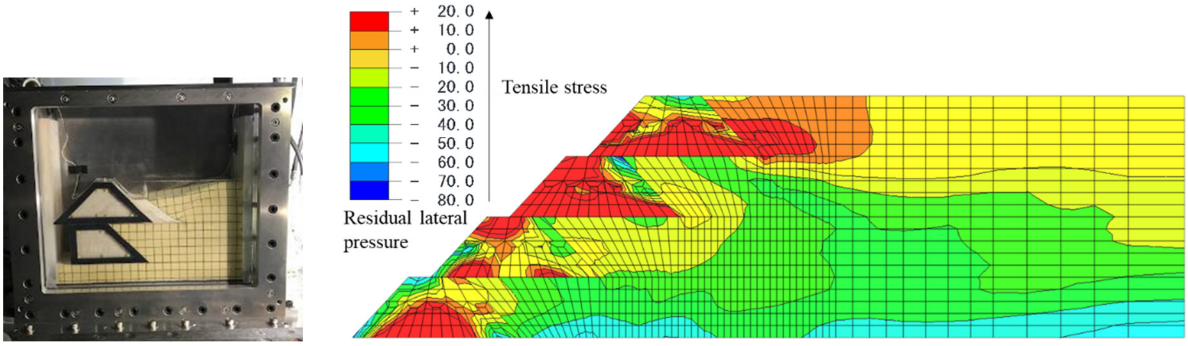
Table 5.4 Input parameters for dynamic analysis

		Dry density (g/cm^3)	Water cont.	Unit wt (kN/m^3)	Shear wave vel. V_s (m/s)	Reference Strain	Max Hysteresis damping h_{max}	Initial shear modulus G_o (kN/m^3)	Coeff. of confining press. n	c (kN/m^2)	φ (°)	Young's modulus E (kN/m^2)	Poison's ratio v
Embankment	Clay	-	-	17.0	100	3.50 E-03	0.10	17335	-	30	20	46227	0.333
	Improved soil	-	-	19.0	400	5.00 E-04	0.10	309994	-	150	0	826651	0.333
Waste	Rigid waste	1.4	25	17.2	175	1.25 E-03	0.15	Overload dependent	0.6	20	35	Overload dependent	0.365
	Soft waste	0.8	25	9.8	95	7.00 E-03	0.11	Overload dependent	0.8	5	45	Overload dependent	0.234
Foundation		-	-	19.0	291.6	4.00 E-04	0.28	164735	-			477732	0.450

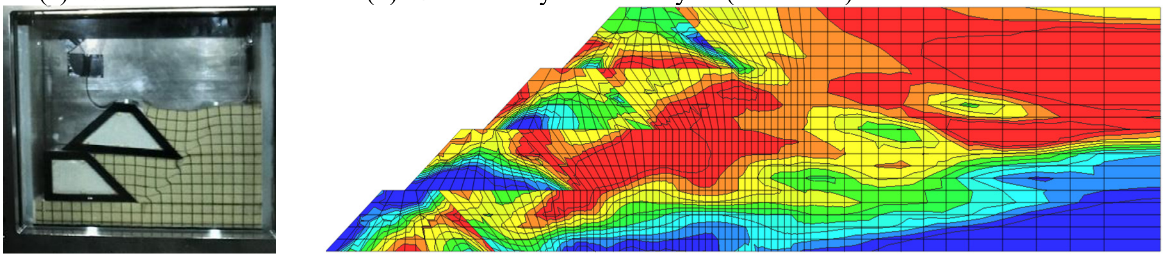
5.4.4 Results and discussion

Qualitative Verification for centrifuge test results

There are some limitations of dynamic analysis carried out for this study. In real case scenario, large dynamic and residual deformation (including remarkable slide of embankment) would have occurred thus making large separation between embankment and landfills after L2 level shaking as shown in centrifuge test. However, in this FEM analysis, small deformation theory was adopted, therefore, it was impossible to reproduce large deformation including large separation of each element. Also, the stress condition of each soil element after failure would become zero in real phenomena, where some cracks may have been formed within the waste layer or in the embankment element. In this analysis, to avoid the un-stability and unrealistic huge calculation time, joint elements were placed only in boundary plane between the embankment and backfill element including touch boundary between adjacent embankments. Therefore, the calculated stress condition within each element after failure became apparently negative (tensile stress). All these limitations of small deformation theory, limited joint element placement, and the calculated unrealistic tensile stress in soil element made us judge only the initiation of active failure observed in centrifuge test by checking whether the lateral earth pressure of landfill element reaches to zero or not from the standpoint of practical use. The stress condition of landfill element after lateral earth pressure becomes zero and associated large deformation could not be traced in this research. Considering these limitations in this analysis, parametric study was carried out with using the above-mentioned simple judgement criteria 'lateral earth pressure becomes zero or not after completion of shaking'. To check the validity of this criteria, comparison between centrifuge model test results and corresponding analytical results was attempted. There are several differences between conditions of centrifuge test and dynamic analysis, material property, embankment model, input motion etc.. Therefore, the comparison was limited only in qualitative evaluation where same mechanism (separation between embankment and back landfill, initiation of active failure in landfill after shaking) was reproduced or not.



(a) With fiber (b) Case 1 in dynamic analysis (with fiber)



(c) Without fiber (d) Case 2 in dynamic analysis (without fiber)

Figure 5.26 Comparison of dynamic analysis residual lateral pressure contour with the centrifuge test results

In Figure 5.26, the contour of residual lateral earth pressure in two dynamic analysis were compared with the centrifuge test results cases 1 and 2 (without and with fiber). Analytical results were chosen in cases which analytical condition was closest to centrifuge test condition (1:1 gradient, rigid embankment). In Figure 5.26, red and ocher colored area shows the active failure (residual earth pressure becomes zero) zone. For centrifuge model test with fiber (Figure 5.26 (a)), there was a huge slide of the first embankment making a failure in the first layer. Similar phenomenon was observed in residual lateral earth pressure contour of dynamic analysis (Figure 5.26 (b)) where development of tensile stress area was observed only near the first embankment and no tensile stress area developed within the deeper layer. Figure 5.26 (d) in dynamic analysis without fiber showed development of large and continuous active failure area same as observed in the centrifuge test (Figure 5.26 (c)). In the centrifuge test, both landfill slopes with and without fiber showed no damage in case of L1 grade input motion (200-gal shaking). It is also same in dynamic analysis as shown in Figure 5.28. Difference in centrifuge model tests seemed to be equivalent to dynamic analysis qualitatively.

The peering of joint element between embankment and back landfill is shown by Figure 5.27 comparing the residual deformation after shaking in without and with fiber cases. For landfill without fiber, all embankments were separated from the landfill layers however, no separation was observed in case with fiber. It also coincided with the differences of residual lateral earth pressure < 0 area between with and without cases. There was also a difference between the residual deformation 'mode' with and without fiber cases. In case without fiber, all embankments seemed to slide to left significantly, separated from back landfill and rotated clockwise, which could not be observed in case with fiber.

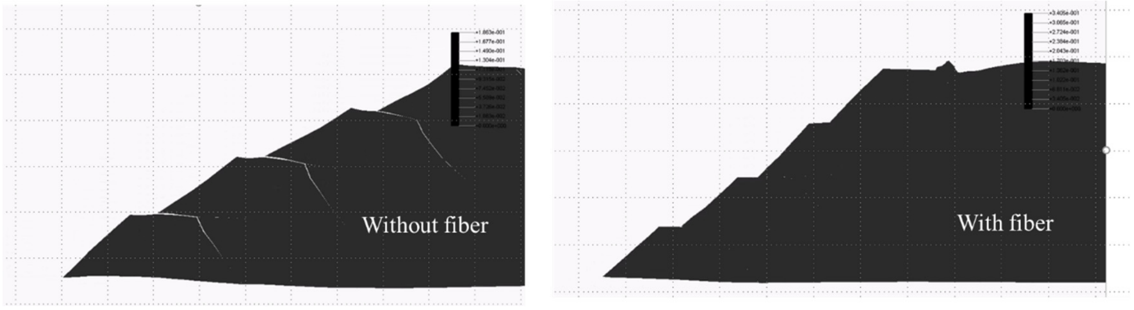


Figure 5.27 The peering of join element for landfill with and without fiber and joint element stress

Parametric study

Figure 5.28 shows the results of sensitivity analysis the four factors affecting it. The factors used in the sensitivity analysis are − (1) presence/absence of fibrous fractions in the waste (2) rigidity of the embankment (assuming cement-improved soil and cohesive soil) (3) input earthquake motion magnitude (L1, L2), and (4) slope gradient. The results can be better understood form Table 5.5. Greater amount of fiber made the slopes more stable. Due to the synergistic effect of low density and tensile resistance, the earth pressure experienced by the embankment was reduced. In this case, the unstable region of the slope was limited not only to L1 but also to L2, and the entire collapse did not occur. The influence of the slope gradient was also negligible. However, in case of highly rigid embankment with fiber, extra care must be taken because the amplification of earthquake motion may occur locally near the surface of the slope of the disposal site, causing deformation on the back surface of the embankment as confirmed in the centrifuge test. On the other hand, for an embankment made of a material with low rigidity such as cohesive soil which does not contain fibrous material (shown in yellow colour in Table 5.5), the ductility and resiliency against strong earthquake is unstably reduced. It was difficult for soft embankment to resist lateral earth pressure from the waste layer without fiber. Even in the case of a gentle slope, the embankment itself may be greatly deformed and destabilized, and maybe collapsed entirely in the form of a circular arc slip similar to the simple design method.

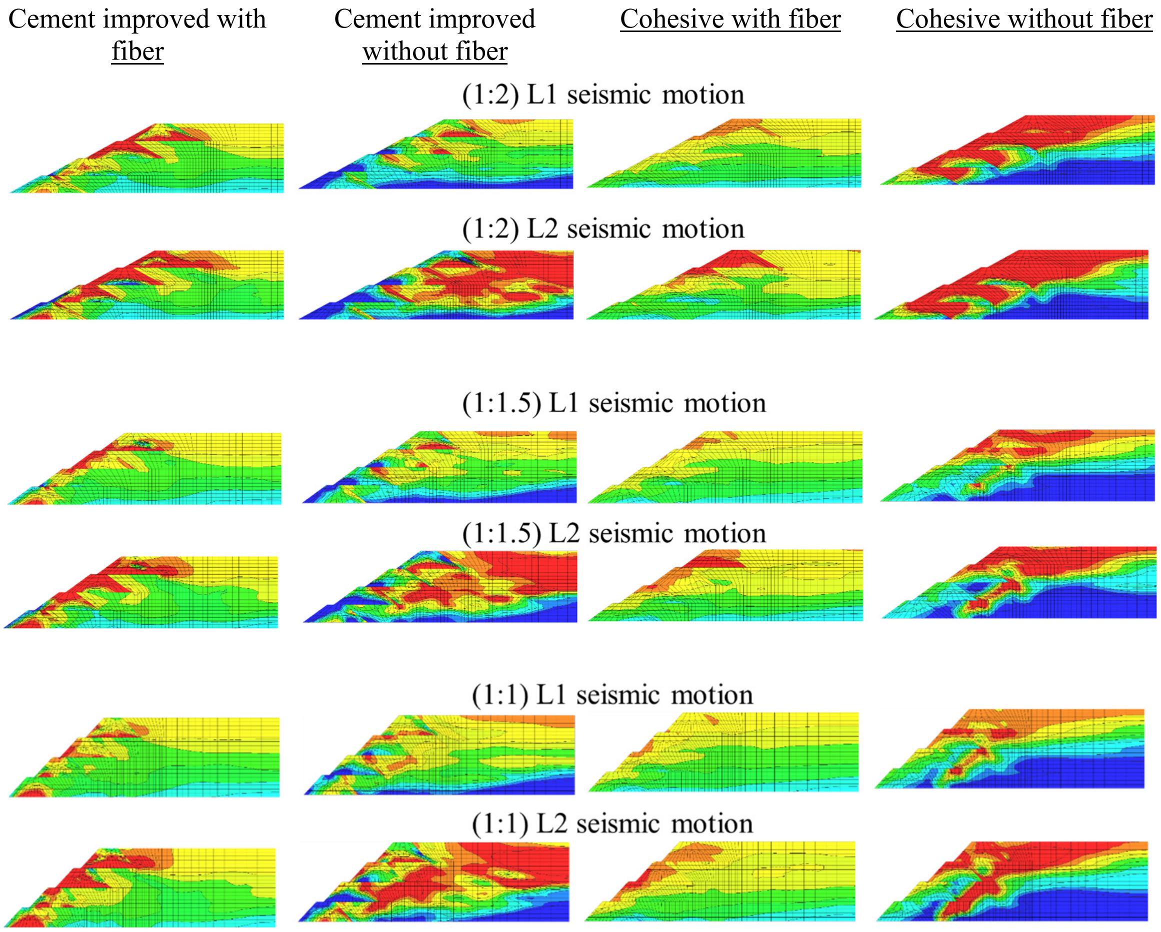


Figure 5.28 The residual earth pressure contours for all the three slope cases (1:1,1:1.5 and 1:2) under L1 and L2 earthquake conditions

Table 5.5 Results summary for sensitivity analysis under 4 conditions

Landfill material	Embankment	Input motion	Effect of slope gradient
With fiber	rigid	L1	Small
		L2	Small
	soft	L1	Small
		L2	Small
Without fiber	rigid	L1	Small
		L2	Large[1]
Without fiber	soft	L1	Large[2]
		L2	

Blue area- slope is stable or little stable,
yellow area- slope becomes unstable or dangerous

[1] gradient is steeper and active failure area is deeper,

[2] for 1:1.5,1:1 slope: gradient is steeper and in L1 to L2 →active failure area is deeper; for 1:2 slope: failure mode changed to surface slip type

Table 5.6 Proposals to current design

Proposals	Design and construction	Summary
Reclamation method of the waste layer	Mixed landfill of waste including fiber	• 'Mixed landfilling' with heavily compacted fiber and soil including the area far enough from the embankment along with the estimated active failure zone of backfill is a better way of reclamation.
Material selection and construction method for embankment	Securing the rigidity of the embankment	• It is better to increase the stiffness of embankment. For soft embankments, slope deforms significantly and whole slope failure may occur even with gentle slope gradient. • For soft embankments, the deformation and slope failure become significant as input motion increases. • Even in the case of mixed waste filling and rigid embankment, some unavoidable damage may occur due to low overburden pressure and amplified motion by the fibrous layer. Some quick remedy method should be prepared for that.
	Controlling the embankment slide during an earthquake	• Measures should be taken to reduce the amount of embankment slide to resist the entire collapse of the embankment-waste slope. • The bottom embankment and the foundation ground should be constructed in such a way that it offers sufficient shear resistance during an earthquake. Geotextiles can be efficiently used to integrate the embankment and the waste.
Waste layer drainage structure	Groundwater level monitoring and drainage structure in the slope of the waste layer	• It is important to monitor the ground water level within back landfills, especially in the vicinity of the slope. • Gravels with good water permeability may be used for covering the soil so that it functions as a horizontal drainage layer. • By constructing a vertical drainage structure, ventilation as well as stability of the slope during an earthquake can be confirmed.

Proposals to current design

Referring to the results of above-mentioned centrifuge test and parametric study, proposals to the current design method of inert waste landfills are listed in Table 5.6. In the field SPT test shown in Figure 5.6, the water level was not observed within the landfill layer and it is common for Japanese waste sites. In general, inert waste landfill material containing plenty of fiber material is assumed to have high permeability, therefore total stress analysis is selected for the current design method. In this research too, the water level was not considered in centrifuge test and dynamic analysis. However, the presence of water inside landfills may decrease the slope stability significantly. Therefore, as indicated in the last column of Table 5.6, the installation of groundwater level monitoring and effective drainage system within the landfill layer especially near the slope area is desirable.

5.5 Conclusions for this chapter

In this study, in-situ investigation, centrifuge model test, and dynamic analysis were carried out for a better slope stability analysis. Field tests such as in-situ density and water content measurement, SPT test, PS logging, repose angle test and direct shear tests were conducted on inert waste landfill sites to determine the physical parameters such as density, water content, N value etc. and strength parameters such as repose angle, internal friction angle, cohesion and shear wave velocity. In-situ density, water content, and shear wave velocity were used as input parameter for dynamic analysis. Models of landfills with and without fibers were made for a centrifuge machine and acceleration within a range of 100-400 gal were applied to check the slope failure behavior and earth pressure on the embankments. For lower values of acceleration (100-200 gal), landfills and embankment were stable, but for higher values (300-400 gal), remarkable damage of slope was observed. In case of rigid embankments (made of cement improved soils), slope failure occurred with slide of embankment due to change in earth pressure from passive to active condition (passive failure mode). Without F.C., complete slide of upper and lower embankment occurred. In case with F.C., overburden pressure in lower layer is larger than upper layer and fibers contributed to tensile resistance thus little damage was observed. Significant slide was observed in the upper embankment for landfills with F.C. for higher values of acceleration (300-400 gal) because of heavy transmission of shaking force from lower (fiber reinforced) rigid landfills. Damage of upper embankment can be repaired easily but this phenomenon should be considered in the design of landfill slopes.

Dynamic FEM response was analyzed using FEM model reproducing the actual slope behavior considering several in-situ conditions. The contour of residual lateral pressure in two cases of dynamic analysis were compared with the centrifuge cases 1 and 2 (without and with fiber). Without fiber case in dynamic analysis showed development of tensile stress in the same places near the embankments where a clockwise rotation of embankments while sinking was observed for centrifuge test. Possibility of complete failure of slope can be predicted from dynamic analysis case 2 without fiber. Little non-linear behavior of embankments and waste layer was observed in cement improved (rigid) condition under small earthquake (L1), but integral behavior of the slope was observed under this condition. For larger earthquake (L2), non-linearity predominated to non-integral behavior and embankments acted against the earth pressure. The severity for L2 earthquake were higher for all the cases. For cement improved (rigid) condition without fiber and under L2 seismic motion, the residual earth pressure spreads up to 3rd layer of the landfill, making the structure more susceptible and it increased with increase of the slope gradient from 1:2 to 1:1. On the other hand, for the cohesive cases without fiber, the slope became more vulnerable with decrease in the slope from 1:1 to 1:2.

Chapter 6

Practical Implications

6.1 General remarks

Practical implications of the research are significant as the quality of research can be determined through its usefulness. Around the world, with the increase in population day by day, construction and demolition of many infrastructures are necessary, and to dispose of the inert waste generated from these works, inert waste landfills are needed. As the inert waste landfill is a new concept to many developing countries, a thorough study on it is a prime need of the present time. From this research, many data on inert waste landfill were obtained through mechanical characterization, slope stability analysis, and leaching characterization. The usefulness of all these results for safe and sustainable management of inert waste landfills is explained as below.

6.2 Mechanical characterization of inert waste landfills

The practical implications of mechanical characterizations of inert waste in the design of an inert waste landfill can be discussed in three stages; namely—planning, landfilling and future expansion, as shown in Figure 6.1. In the planning stage, since there is no actual waste present, the data presented in this study can be used to design a new inert waste landfill. As the data obtained in this study are scattered due to the heterogeneity of the waste material, conservative values may be used for design or to analyze the slope stability. In the landfilling stage, inert waste material is already present in the landfill and the composition of the waste is known. At this stage, the ranges of the strength parameters values become narrower than the planning stage, but there is still a need to check the stability of the landfill. Shear strength parameters c and φ can be estimated from the waste composition or by conducting simple and quick tests to use the correlations developed in this study. Moreover, using specific gravity estimation method, the material properties and packing condition of the inert waste can be estimated quickly to ensure better strength characterization. At last, in the future expansion stage of an existing inert waste landfill, more detail-oriented tests such as direct shear tests can be conducted to obtain more precise shear strength parameters to attain better slope stability. The strength parameters can be directly obtained using these experiments. Although the sample size used were smaller, the mechanical characterization of inert waste conducted in the laboratory is beneficial too. The sample used for laboratory test were collected from the actual landfill sites; therefore, it has a great value among all the data collected for the inert waste materials. The compared data of the in-situ tests and laboratory tests can be used in the planning stage. Moreover, difficult in-situ tests can be avoided by conducting laboratory experiments for non-critical analysis.

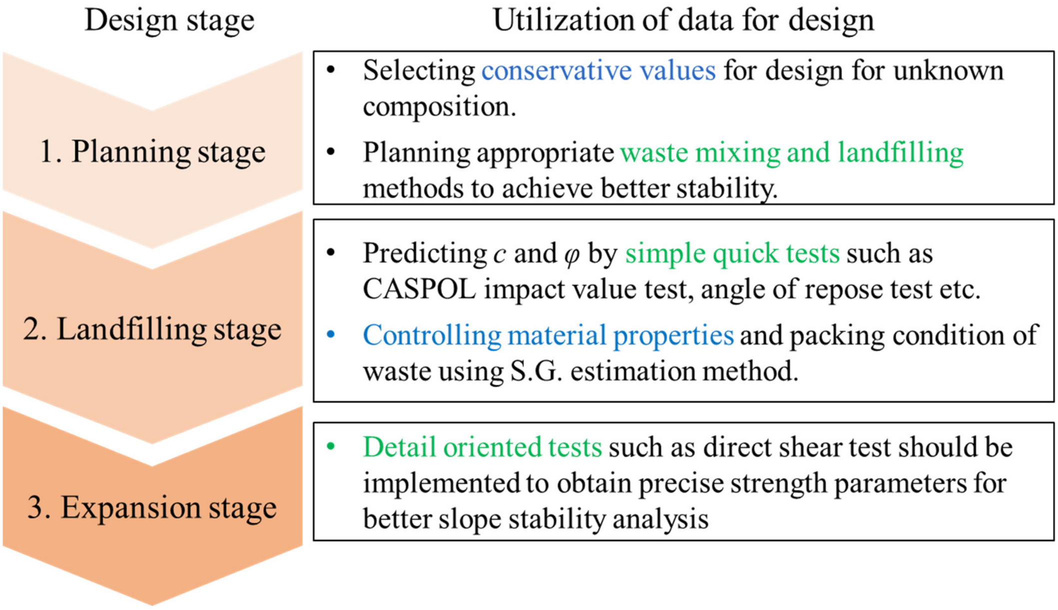


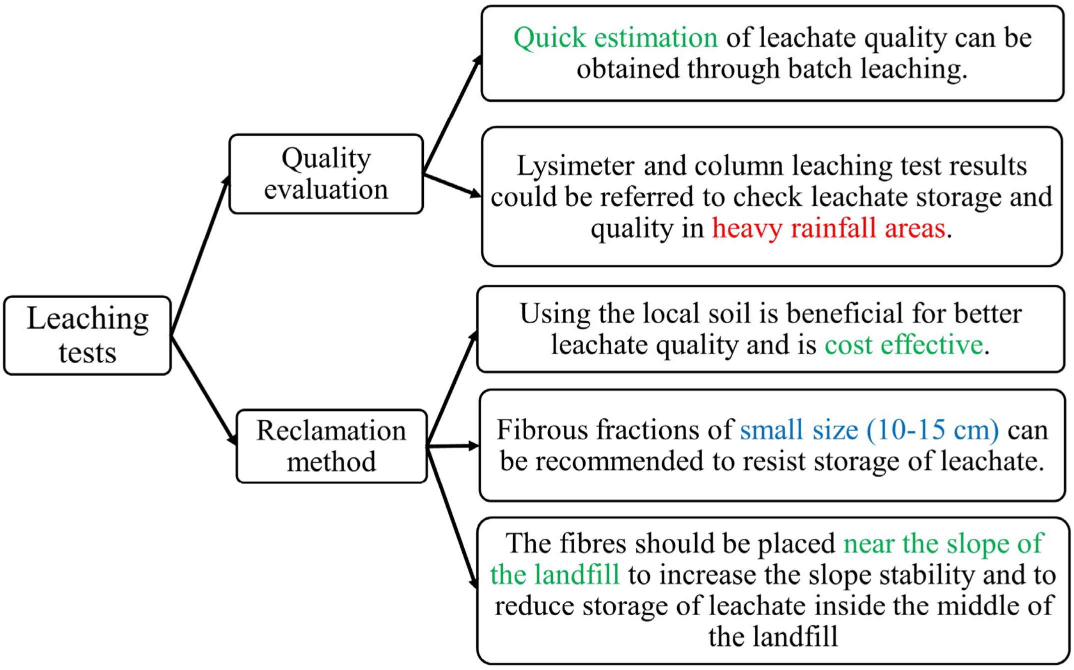
Figure 6.1 Utilization of the mechanical characterization data

The results from the mechanical characteristics showed that if the fibrous content in inert waste is within a specific limit, the shear strength of inert waste was higher than the municipal solid waste. Moreover, an increase in the fibrous content in inert waste demonstrated higher values of shear stress under earthquake condition. Therefore, to get better strength and stability, inert waste with a specific amount of fibrous content should be used while landfilling. By that way, a steeper slope can be designed without compromising the bearing capacity. If the bearing capacity of the landfill is strong enough, then the landfills can be reused for construction of different types of temporary or permanent facilities. A steeper slope in landfill results in increasing the storage capacity of the landfills, which in turn reduces the burden of finding more land areas for construction of new inert waste landfills. As the population of the world is increasing day by day and availability of lands for use are decreasing, an inert waste landfill with high bearing capacity and steeper slope uses less land and is sustainable. For new construction of a landfill, all kinds of activities such as using machines, transporting different construction materials, human activities etc. directly or indirectly affect the environment. Therefore, utilizing the data from mechanical characterization can reduce the impact on the environment and can help to manage the inert waste with sustainability. However, while landfilling, it may be challenging to maintain a specific amount of fibrous content in the inert waste. If the fibrous fractions are less, in that case, more fibrous fractions should be placed near the slope area to increase the slope stability. If the fibrous fraction is huge, then the mixing them with the soil obtained from the excavation work (during the construction of landfills) may increase the stability as well as bearing capacity. In that case, the mechanical characterization of the inert waste materials should be conducted again.

6.3 Leachate characteristics of inert waste

Leaching test results illustrate benefits regarding the environmental safety and landfilling method as shown in Figure 6.2. Batch leaching tests can be used for a quick estimation of leachate quality. However, the results obtained from batch leaching tests are just an approximate idea of the contaminants present in the waste leachate or the sorption capacity of the soil. Lysimeter tests or laboratory column tests results are more precise than the batch test as the real site condition can be reproduced through these tests. For areas with heavy rainfall, leaching tests are useful to observe the leachate flow rate and storage of leachate inside the landfill. The lysimeter test and laboratory column leaching test confirmed the sorption of the heavy metals or other contaminants by soil layer. Therefore, using the soil excavated during the inert waste landfill construction will be a cost-effective solution to have a better leachate quality.

Leachate behavior is dependent on the size of waste materials and the way of reclamation. The fibers should be placed near the slope of the landfill to increase the slope stability and to reduce storage of leachate inside the middle of the landfill. While landfilling, high compaction should be carried out to remove the voids present as much as possible. The lesser numbers of voids reduce the possibility of leachate storage inside the landfill. The safety from the storage of leachate inside the landfills can be confirmed by reducing the size of the fibrous fractions in inert waste landfills. Proper crushing of inert waste materials can be recommended for that. The size of fibrous fraction should be smaller (10-15 cm) to eradicate the storage of water by large-sized fibrous content. Adding soil layers can assist in sorption of contaminants present if any, and acid neutralization. The used soils are the easily available natural soil obtained from the landfill site, obtained from the excavation work conducted during the construction of landfills. Therefore, it reduces the burden of transporting soils from other places which affects the environment. However, precaution should be taken while using the soils. Before use, the soil should be checked for any contaminants such as heavy metal or organic matter etc. to avoid the negative effect from it. Presently, some inert waste landfills in Japan use a cover soil layer of 50 cm for every 2 m waste buried with waste: soil ratio as 1:4. The waste: soil layer used for this research was 1:6 for lysimeter and 1:8 for laboratory column tests. It means that the thickness of the soil layer can be reduced for inert waste landfills and the remaining soils can be used for other construction works as raw materials for a sustainable environment.



Quick estimation of leachate quality can be obtained through batch leaching.

Lysimeter and column leaching test results could be referred to check leachate storage and quality in heavy rainfall areas.

Using the local soil is beneficial for better leachate quality and is cost effective.

Fibrous fractions of small size (10-15 cm) can be recommended to resist storage of leachate.

The fibres should be placed near the slope of the landfill to increase the slope stability and to reduce storage of leachate inside the middle of the landfill

Figure 6.2 Utilization of leaching test results

6.4 Slope stability analysis of inert waste landfills

The slope stability analysis was conducted using a common and conventional analytical method which can be easily used by the practical engineers. For seismic prone areas, the results of the slope stability analysis can be advantageous while designing the embankments of inert waste landfills. The results showed the variation in earth pressures during earthquake condition, which can be used for cautionary advices regarding the construction of retaining walls. As the slope stability analysis confirms the stability even under earthquake condition, a proper reclamation method can be recommended using the results. The utilization of slope stability analysis is shown in Figure 6.3.

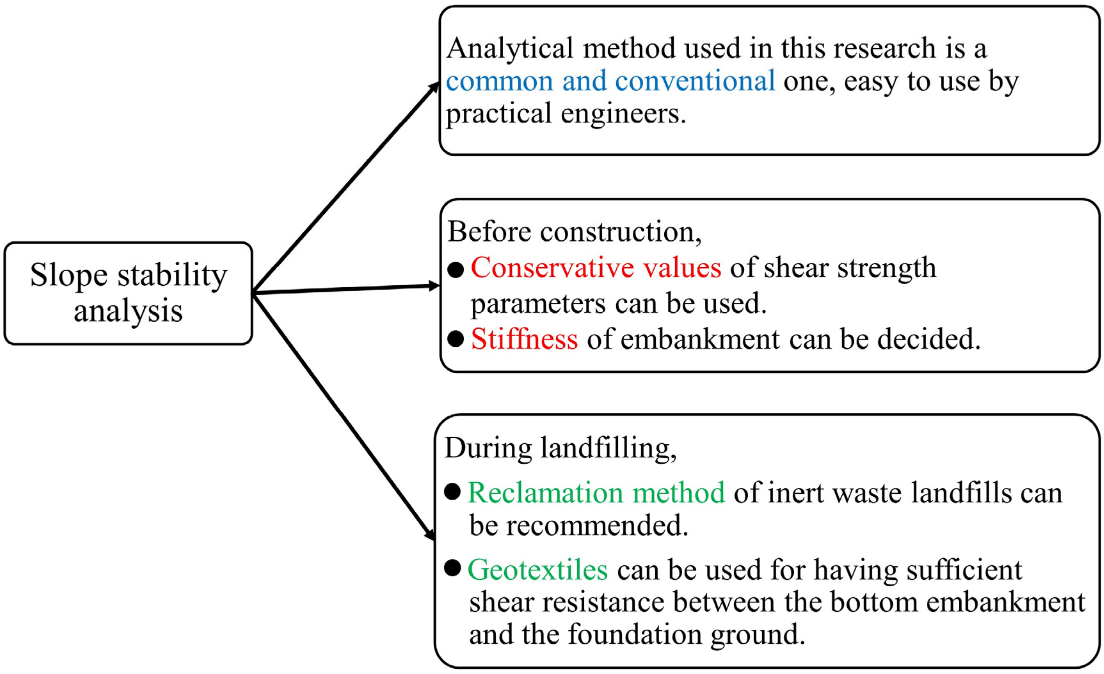


Figure 6.3 Utilization of slope stability analysis

In slope stability analysis, the positive effect of fiber inclusion in waste was observed. Therefore, 'mixed landfilling' of inert waste with fiber and soil material was recommended. Heavy compactions in areas far from the embankment and in the estimated active failure area of backfill make the landfill more stable and safer. If inert waste landfills don't have any fiber, half compacted, and the embankment is also not stiff, deformation and slope failure become significant with an increase in input motion and slope gradient. In that case, the landfill slope has no resilience to a strong earthquake. Stiffness of embankment by cement improving may be a better alternative to resist the whole slope failure. For countermeasures of the embankment slide, artificial geotextile in the top layer can be used, which helps in increasing frictional resistance within the landfill. Another countermeasure is increasing the friction between the top and second embankment. In the field, the roughness of boundary can be increased by 'raking' which means digging several ditches on the surface of 2nd embankment by construction machine and constructing the top embankment on it. In the previous field studies on inert waste landfill by Yamawaki et al. (2013), the water level was not observed within the landfill layer, and it is common for Japanese waste sites. In general, inert waste landfill material is assumed to have high permeability. In this research, too, the water level was not considered in the centrifuge test and dynamic analysis. However, the presence of water inside landfills may decrease the slope stability significantly. Therefore, it is crucial to monitor the groundwater level within back landfills, especially in the vicinity of the slope. By constructing a vertical drainage structure, ventilation, as well as stability of the slope during an earthquake, can be confirmed.

Chapter 7

Conclusions

In this research, studies on the mechanical and leaching characteristics of inert waste were carried out and slope stability analysis was conducted to observe seismic behavior of the inert waste landfills. For mechanical characterization, in-situ as well as laboratory strength characteristics and basic physical parameters of the inert waste were studied. To understand the leaching behavior, three types of leaching tests, which are lysimeter test, laboratory column leaching test, and batch leaching test were conducted using the inert waste samples collected from the landfill sites. For slope stability analysis, centrifuge model test and FEM dynamic analysis on landfill models under small and large earthquake conditions were performed, and the two methods were compared qualitatively. The input parameters used for FEM dynamic analysis were determined from the in-situ tests. The results demonstrated that within a specific limit, the fibrous fractions present in the inert waste improved the shear strength of the waste and showed improvement in the slope stability during earthquake condition. The leaching test confirmed the safety of the quality of the leachate generated in inert waste. Possible storage of leachate in large fibrous fractions inside the inert waste landfill can be reduced by using fibrous fractions of 10-15 cm size. Therefore, in place of the existing slope of the inert waste landfills in Japan, a steeper slope can be recommended to increase the waste storage capacity of the landfill. The individual conclusions for the mechanical characterization, leaching tests, and slope stability analysis are summarized below.

Mechanical characterization of inert waste

<u>In-situ tests</u>

In this research, strength characteristics and basic physical parameters of inert waste landfills were studied. Field tests such as composition analysis, basic physical properties, angle of repose, CASPOL impact value test and in-situ direct shear test were conducted at the locations to know mechanical properties of the inert waste materials. From the results of the field tests, the following conclusions could be drawn:

- Three main components were found as: 3.6 to 54% of fibrous content (consisting of ‘plastics’ and ‘other fibers’ > 20 mm), 13 to 45% of granular content (consisting of ‘rocks’ and ‘glasses and potteries’ > 20 mm) and 43 to 74% of soil-like content (≤ 20 mm).
- Increases in soil-like and granular fractions showed significant increase in dry density up to 1.8 times. Dry density decreased with increase in fibrous content under 31%.
- Percentage air voids was lower for older landfills. The water content increased and percentage air voids decreased with increase in fibrous content and age after reclamation.
- Impact value increased with increase in dry density and soil-like content. Higher the dry density, voids were lesser and bearing capacity became more. Decomposition of biodegradable waste and water penetration through the landfill with age after reclamation were considered to be the reason for lower impact value of older landfills.
- For all the locations, angle of repose after avalanche (α_a) was within the range of 34-44°.
- Cohesion values were found within the range of 2-21 kN/m^2 and internal angle of friction was found within the range of 22-59°. With increase in dry density, cohesion increased and friction angle decreased.
- The inert waste strength parameters gave higher shear strengths than the municipal solid wastes, particularly for landfills having fibrous fractions ranging from 14% to 31%.
- The correlation calculated for c and φ with impact value for inert waste landfill within 10 years of age are $c = 4.10\ I_a - 21.32$ and $\varphi = -4.61\ I_a + 82.37$ where, c = cohesion (kN/m^2), φ = internal angle of friction (°) and I_a = impact value. With increase in the impact value, c increased and φ decreased.
- The specific gravity values estimated for fibrous, granular and soil fractions in the inert waste landfills were 1.0, 2.60 and 2.80 respectively.

Laboratory direct shear test

In this research, the effect of fibrous fractions on shear strength properties were evaluated by laboratory direct shear tests. The vital results observed for this study are

- The internal friction angle first increased, then decreased with an increase in the proportion of fibrous materials to a certain extent
- Cohesion first decreased and then increased with increase in fibrous content.

- Good agreement of results could be observed between the onsite and the laboratory shear strength parameters within a specific limit of fibrous content.

Laboratory triaxial test

laboratory compaction tests and triaxial tests were carried out on the inert waste materials (separating the fibrous fractions from the waste) and mixed with artificially made fibrous contents at different ratio of weights to understand the change in mechanical properties of inert waste due to variation in fibrous content. The significant results achieved are

- Dry densities of inert waste decreased with increase in fibrous content.
- In triaxial test, deviatoric stresses increased with increase in confining pressure and fibrous content.
- With increase in axial strain under confining pressures of 60 and 90 kPa, the volumetric change of 0% F.C. showed similar behavior as dense sand and that of 1% F.C. was similar to loose sand.
- For 0.5% and 1% fibrous content under high confining pressure, deviatoric stress increased after a certain axial strain. Therefore, under high axial strain condition, inert waste with fibrous content may show higher shear resistance.

Leaching Tests

Lysimeter leaching test

In lysimeter tests, drainage behavior of leachate was studied and possibility of presence of contaminants were checked. Change in parameters such as dissolved total organic carbon (TOC), total nitrogen (TN), Sulfate ion (SO_4^{2-}) with respect to the liquid-solid ratio (L/S) was observed for inert waste collected from landfills.

- Sorption of dissolved parameters in the leachate water was observed for waste with soil layer or soil mixed with waste.
- In case of highly compacted waste, deterioration in quality of leachate was observed, but the values of most of the contaminants were found within the standard limit.
- The heterogeneity in basic property (ex; size and shape) of inert wastes showed the variations in the quality of leachate.

Laboratory column leaching test

Laboratory column leaching tests were conducted with columns having 2% and 10% fibrous content to know leaching characteristics of inert waste landfills due to variation in fibrous content. The significant results observed are as follows

- Drainage of water was higher for small sized high fibrous content (10% F.C.). With high fibrous content, the density became lower which made the drainage higher and water contact time lesser.
- The water storage and EC were lower for the column with small sized high fibrous content (10% F.C.) than that of small sized low fibrous content (2% F.C.).
- Higher fibrous content in the waste materials does not store leachate if they are smaller in size.
- The presence of organic matters was confirmed in the inert waste from the TOC test, but the value was found to be within the standard limit.
- Heavy metals such as As and boron were also lesser in case of small sized high fibrous inert waste materials.
- Soil layer installation seemed to be an effective solution for sorption of heavy metals etc. and buffering capacity.
- With increase in the depth of waste, pH values and heavy metals increased.

Laboratory batch leaching test

Laboratory batch test was conducted to have a quick analysis of the collected inert waste and soil sample used for laboratory column leaching test. The significant results are

- The waste and soil both were classified as moderately reduced with Eh values of 302.2 mV and 350.47 mV respectively.
- Both waste and soil were highly alkaline in nature with pH values of 10.29 and 9.34 respectively.
- Heavy metals in the soil leachate were higher than waste leachate. The soil seemed to be naturally contaminated.
- Leaching behaviors under acidic rainfall were different for waste and soil.

Slope stability analysis

Centrifuge model test

In this study, models of landfills with and without fibers were made and tested in a centrifuge machine and acceleration within a range of 100-400 gal to check the slope failure behavior and earth pressure on the embankments. The results obtained are as follows

- For lower values of acceleration (100-200 gal), landfills and embankment were stable, but for higher values (300-400 gal), remarkable damage of slope was observed.
- In case of rigid embankments, slope failure occurred with slide of embankment due to change in earth pressure from passive to active condition (passive failure mode).
- Without F.C., complete slope failure of upper and lower embankment occurred. In case with F.C., overburden pressure in lower layer is larger than upper layer and fibers contributed to tensile resistance thus little damage was observed.
- Significant slide was observed in the upper embankment for landfills with F.C. for higher values of acceleration (300-400 gal) because of heavy transmission of shaking force from lower (fiber reinforced) rigid landfills. Damage of upper embankment can be repaired easily but this phenomenon should be considered in the design of landfill slopes.

Dynamic FEM analysis

Dynamic FEM response was analyzed using FEM model reproducing the actual slope behavior considering several in-situ conditions. The contour of residual lateral pressure in two cases of dynamic analysis were compared with the centrifuge cases 1 and 2 (without and with fiber). The important results obtained for dynamic analysis are listed below

- Without fiber case in dynamic analysis showed development of tensile stress in the same places near the embankments where a clockwise rotation of embankments was observed initiating sinking of embankments in case of centrifuge test.
- Little non-linear behavior of embankments and waste layer was observed in cement improved (rigid) condition under small earthquake (L1), but integral behavior of the slope was observed under this condition.
- For larger earthquake (L2), non-linearity predominated to non-integral behavior and embankments acted against the earth pressure.

- The severity for L2 earthquake were higher for all the cases.
- For cement improved (rigid) condition without fiber and under L2 seismic motion, the residual earth pressure spreads up to 3rd layer of the landfill, making the structure more susceptible and it increased with increase of the slope gradient from 1:2 to 1:1.
- On the other hand, for the cohesive cases without fiber, the slope became more vulnerable with decrease in the slope from 1:1 to 1:2.

Recommendations for future research

From this research, a large set of databases for inert waste materials from inert waste landfills inside Japan was obtained. The inert waste concept is new to many developing countries. Research on inert waste landfills is limited as most of the countries do not have inert waste landfills. More data collection is needed for future research and construction of new inert waste landfills around the world. From this study, the effect of composition on the mechanical properties was clear. There is still a need to conduct detailed studies on compositions of inert waste landfills around the world. It was observed that heterogeneity in the basic property (ex; size and shape) of inert wastes affected the mechanical characteristics as well as leaching characteristics of the inert waste samples. In the future, test results can be obtained, considering more detailed basic properties of the samples to evaluate mechanical and leaching properties significantly. Scale effect of the direct shear test should be studied thoroughly. In this research, the water level was not considered in the centrifuge test and dynamic analysis. However, the presence of water inside landfills may decrease the slope stability significantly. Slope stability should be carried out considering the water level to ensure better safety. Therefore, the installation of groundwater level monitoring and effective drainage system within the landfill layer, especially near the slope area, is desirable. Last but not least, to understand the leaching behavior of inert waste materials under acidic conditions, column leaching tests with inert waste materials under acidic rainfall conditions can be conducted for a long period of time.

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