STUDY ON INNOVATIVE MULTI-LAYER DESIGN
OF LANDFILL COVER BARRIER LAYER

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Division of Engineering Systems and Technology
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STUDY ON INNOVATIVE MULTI-LAYER DESIGN OF LANDFILL COVER BARRIER LAYER

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by

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ABSTRACT

Over the past several decades, technologies have developed and advanced to enable the effective covering of landfills in accordance with environmental goals. Alternative landfill covers are still a new idea that has not been officially written into any policy or regulation in many countries. The objective of this study is to design an innovative multi-layer barrier as a barrier layer material of cover system. The study program includes: (1) investigate the geotechnical properties and desiccation cracking behavior of soil-fiber mixtures as a material for landfill barrier layer of cover system, (2) propose the design criteria of the soil-fiber mixtures as a barrier layer material based on the optimum fiber content criteria, and (3) investigate the effect of multi-layer barrier in reducing the quantity of rainwater percolating through the barrier layer. The laboratory test was performed in accordance with the ASTM standards. The materials used in this study are volcanic soil (Akaboku) and polypropylene fiber as an additive.

In order to investigate the geotechnical properties of the soil-fiber mixtures, various laboratory tests were conducting includes compaction characteristics, strength, hydraulic conductivity, and desiccation crack. The inclusion of fiber additive in the soil improves the geotechnical properties of the soil specimens. The contribution of fiber to the compaction characteristics increases with increasing in the fiber contents. The fiber inclusion increased the compressive strength, ductility, and decreased the loss of the post-peak strength. The energy absorbing capacity also increases, resulting in a higher ductility in the post-peak region. The tensile strength of the soil-fiber mixtures also improved, this is mainly due to the increase in the adhesion force as the surface contact area between the soil and fibers increase by increasing the fiber content. The highest compressive and tensile strength of soil-fiber mixtures occurred at the highest dry density of the soil specimen due to the rearrangement and dense packing of the particles. Moreover, the shear strength of the compacted soil-fiber mixture increased and was found that the improvement of shear strength mainly controlled by the cohesion. The hydraulic conductivity in the range of fiber contents used in this study is within the acceptable limit and can satisfy the requirements.

The desiccation crack tests were performed in order to investigate the desiccation cracking behavior of soil-fiber mixtures. Fiber inclusion increased the volumetric shrinkage strain reduction significantly. The volumetric shrinkage strain decreased
approximately 51% within the range of fiber contents used in this study. With the fiber additives, crack was significantly suppressed. The crack intensity factor (CIF) decreased almost three orders of magnitude with increasing in the fiber content. This is mainly due to the interaction of soil particles and fibers, which enhanced the resistance against crack.

The superimposition method was used to develop the overall acceptable zone (AZ) with respect to the five design parameters, such as compaction characteristics, unconfined compressive strength, tensile strength, cohesion, hydraulic conductivity, and crack intensity factor. The CIF can be considered to be the second most significant factor after hydraulic conductivity controlling the shape of the overall AZ. The optimum fiber content that was necessary to satisfy the condition of design criteria (overall AZ) introduced in this study was found to be 0.8%. The results of this proposed design criteria illustrate that is possible to use the compacted soil-fiber mixture with increasing in the strength, low hydraulic conductivity, and to simultaneously produce a compacted material without cracking.

The evaluation on the water interception performance of multi-layer barrier layer indicated that the average quantity of the water percolating is less than 2 mm/hr, which equals approximately 2% of the total precipitation applied. More than 85% of the precipitation could be intercepted by the multi-layer barrier layer as a surface runoff. It is indicated that the barrier layer could effectively intercept the precipitation. Furthermore, the barrier layer also appeared effectively to store water. The average water storage capacity for the multi-layer barrier layer was 13 mm, which equal approximately 13% of the precipitation. The amount of water stored in the multi-layer barrier layer indicated that during the dry periods, the barrier layer could provide moisture to prevent the desiccation cracking problem. Moreover, the water stored is also believed that could provide humidity to keep the barrier layer temperature remained constant.

The good performance of soil-fiber mixtures as a material for barrier layer and the significant intercept behavior of the multi-layer barrier in this study indicate that there is some potential for the use of multi-layer barrier layer in landfill cover system. The application of this proposed design could contribute to the sustained development of the landfill technology especially in Japan.
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Dedicated to

My Parents, my wife and my daughter
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English letter symbols

\begin{itemize}
  \item \textit{a} Width of flattened portion
  \item \textit{AC} Desiccation crack area
  \item \textit{A_t} Total surface area of soil specimen
  \item \textit{AET} Actual evapotranspiration
  \item \textit{AZ} Acceptable zone
  \item \textit{c} Cohesion
  \item \textit{C} Surface runoff coefficient
  \item CIF Crack intensity factor
  \item CSLF Compacted soil layer with fiber additive
  \item \textit{d} Basal spacing
  \item \textit{D_{max}} Maximum crack depth
  \item \textit{E} Elasticity modulus
  \item \textit{E_{50}} Secant modulus at 50\% of the unconfined compressive strength
  \item \textit{F} Applied force
  \item \textit{FC} Fiber content
  \item \textit{i} Summation indices
  \item \textit{j} Summation indices
  \item \textit{k_s} Saturated hydraulic conductivity
  \item \textit{k (\theta i)} Unsaturated hydraulic conductivity
  \item \textit{l} Thickness of specimen
  \item \textit{L} Lateral drainage from internal drainage layer
  \item \textit{L_0} Initial length of specimen
  \item \textit{L_l} Length between two points at failure
  \item \textit{\Delta L} Length difference
  \item \textit{m} Number of increments of \theta
  \item \textit{MSW} Municipal solid waste
\end{itemize}
n Order of reflection
OMC Optimum moisture content
$TI$ Toughness index
$P$ Precipitation
$PERC$ Percolation through the cover system
$q_u$ Unconfined compressive strength
$r$ Ratio between stress and unconfined compressive strength ($\sigma / q_u$)
$R$ Runoff
$S$ Saturation degree
$V$ Total volume of the soil specimens
$\Box V$ Change in volume
$w$ Water content
$W_s$ Water storage capacity
$W_0$ Initial weight of soil specimen
$W(t)$ Weight of soil specimen at each time
$w_0$ Initial water content of soil specimen
$w(t)$ Water content of soil specimen at each time
$\Delta W_{\text{surface}}$ Change in water storage at surface
$\Delta W_{\text{foliage}}$ Change in water storage on plant foliage
$\Delta W_{\text{soil}}$ Change in water storage in cover system soil
$x$ Flattening ratio
$y$ Vertical distance between the flattened portions at failure

**Greek letter symbols**

$\varepsilon_{50}$ Strain which corresponding to 50% of unconfined compressive strength
$\varepsilon$ Strain
$\varepsilon'$ Normalized strain
$\varepsilon_f$ Strain at failure
$\varepsilon'_r$ Normalized strain at $\sigma / q_u$
$\varepsilon_{fT}$ Strain at failure of tensile strength
\( \gamma_d \)  Dry unit weight
\( \gamma_{d(0)} \)  Initial value of dry unit weight
\( \gamma_{d(t)} \)  Normalized dry unit weight at each time
\( \gamma_{d\ max} \)  Maximum dry unit weight
\( \lambda \)  Wave length
\( \Theta \)  Deflection Angle
\( \theta \)  Volumetric water content
\( \sigma \)  Stress
\( \sigma_T \)  Tensile stress
\( \sigma_1 \)  Normal stress
\( \phi \)  Internal friction angle
\( \phi \)  Diameter
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1.1 General

An engineered landfill is a controlled method of waste disposal. The site of the landfill must be geologically, hydrologically, and environmentally suitable. A landfill is not an open dump. Nuisance conditions associated with an open dump such as smoke, odor, unsightliness, insect and rodent problems are not present in properly designed, operated, and maintained sanitary landfill. Professional planning and engineering supervision are required. A landfill has a carefully designed and constructed envelope that encapsulates the waste and that prevents escape of leachate into the environment. The envelope consists basically of a cover and bottom liner (Qian et al. 2001).

Cover systems are used at landfills and other types of waste management units (e.g. waste piles, mine tailings piles, surface impoundments) to contain waste and any waste byproducts (e.g. leachate, acid mine drainage, gas). Cover systems are also used to meet erosion, aesthetic, and other end-use criteria for waste management sites. Cover systems for waste sites may involve only a single soil layer or multi-component system of soil and geosynthetic layers, placed over a hazardous waste landfill (Bonaparte and Yanful, 2000). Usually, waste containment facilities are required to protect the peripheral geoenvironment from being polluted by the migration of waste leachate. Effective design of the waste containment facilities means not only to install bottom liner, cutting down the leachate
produced but also to establish the landfill cover system, preventing the infiltration of rainwater and surface water into the waste layer and to minimize the generation of waste leachate (Kamon and Katsumi, 2001).

1.2 Barrier Systems

At present cover system designs are based on one or more of three different principles for preventing or minimizing water percolation into waste. Hydraulic barrier uses a low permeability physical barrier to impede the downward migration of water into the waste. Hydraulic barrier material most commonly include compacted clay layers (CCLs), geosynthetics clay liners (GCLs), geomembranes, and combination of these materials. Furthermore, capillary barrier consists of one or more layers of finer-grained soil overlying one or more layers of coarser-grained soil. Capillary barrier either: (i) store water by increased moisture content in the finer-grained soil for subsequent evapotranspiration, or (ii) divert infiltrating water via unsaturated lateral flow in the fine-grained soil. Evapotranspirative barriers are covers that consist of a thick layer relatively fine-grained soil capable of supporting vegetation Evapotranspirative barriers exploit two characteristics of fine-grained soil: (a) significant soil water storage capacity and (b) low hydraulic conductivity even at high degrees of saturation. Moreover, different barrier types may be combined in a single cover system. For example, a capillary barrier may be constructed beneath and evapotranspirative barrier (Bonaparte and Yanful, 2000).

Cover system can be constructed with a wide variety of configurations of soil and geosynthetic layers to satisfy project-specific design criteria. For a municipal solid waste (MSW) landfill, the CCL hydraulic barrier and GCL hydraulic barrier commonly used. The cover system has benefit to prevent and minimize percolation and thereby reducing the potential for waste liquid generation, e.g. leachate, acid mine drainage.

1.3 Problem Statement

As municipal solid waste (MSW) decomposes, it produces a blend of several gases, which is primarily composed of methane (about 40 – 60%) and carbon dioxide (CO₂). A methane gas (CH₄) is a greenhouse gas and the release of the methane gas to the atmosphere creates
some global warming problems. According to the USEPA (1999a), the landfills are the dominant source of the methane emission, accounting approximately 37% of the United States total in 1997. Many factors determine the gases given off by decomposing garbage at landfills. The weather conditions have a large effect on the rate of gas generation in landfill. Increased temperature allows the bacteria to grow faster and increases gas generation. Moisture also allows the bacteria population to grow and this moisture can be from precipitation. Increased humidity also appeals to bacteria. Moreover, the frequent rain and storms can cause a large increase in gas production. Therefore, an innovative design of barrier layer was proposed in order to overcome the problem mentioned above.

In the dry season, the desiccation cracking problem commonly encountered in landfill. Desiccation of clay liners is a major factor affecting landfill performance. Desiccation leads to the development of shrinkage cracks. Cracks provide pathway for moisture migration into the landfill cell which increases the generation of waste leachate, hydraulic conductivity, and ultimately increase the potential for soil and groundwater contamination (Miller et al. 1998). Moreover, Desiccation cracks can also form macrospores. This phenomenon is important in environmental applications due to its impact on groundwater and vadoze zone transport rates. Utilization of fiber additive is believed could suppress the desiccation crack encountered in landfill cover system.

1.4 Objectives and Scope of the Study

The main objectives of this study are as follows:

1. To evaluate the geotechnical properties of soil-fiber mixture. The parameters for the design of cover barrier layer such as compaction characteristic, unconfined compressive strength, cohesion, internal friction angle, tensile strength and hydraulic conductivity were investigated to evaluate the suitability of the soil-fiber mixture being used as a material for landfill cover barrier system for future uses during the post-closure period of landfill.
2. To investigate the influence of fiber additives on the compacted Akaboku soil potentially used as a material for landfill cover barrier system. The laboratory tests were conducted to investigate the effects of fiber additives on the desiccation crack
and volumetric shrinkage behavior of compacted Akaboku soils.

3. To propose the design criteria of multi-layer cover barrier layer based on the optimum fiber content. Suggestions are made for overall acceptable zone based on the five design parameters considered within which compacted test specimens will have low hydraulic conductivity ($\leq 1.0 \times 10^{-5}$ cm/sec), have a suitable mechanical properties for structural integrity, and resistant to cracks due to desiccation.

4. To design an innovative multi-layer barrier layer using compacted soil layer with fiber additive (CSLF). In this study, a new barrier system technology was proposed to minimize the infiltration of rainwater into waste and maintain the water stored in the barrier layer.

The dissertation comprises mainly of seven chapters, the research flow and content of this dissertation is given in Figure 1.1. Chapter 1 clarifies the objectives and the contents of the dissertation. Chapter 2 reviews the present condition of waste managements and landfill technologies and landfill cover system. Chapter 3 evaluates the geotechnical properties of soil-fiber mixtures as a material for barrier layer. The geotechnical properties include compaction characteristics, compressive strength, tensile strength, shear strength, and hydraulic conductivity were evaluated. Chapter 4 discussed on the desiccation cracking behavior of soil fiber mixtures with various fiber contents. The laboratory experiment was set up with equipment to simulate the condition in the field. Chapter 5 shows the proposed design criteria of soil-fiber mixtures based on the optimum fiber content potentially used as a material for landfill barrier layer. The superposition method is used to define the acceptable zone of all parameters used to meet the design criteria. Chapter 6 shows the proposed innovative multi-layer barrier layer of cover system. The water intercept performance and water storage capacity of the new design of barrier layer are discussed. Moreover, the relationships of water storage capacity and volumetric water content in order to predict the water storage capacity is introduced. Chapter 7 summarizes the entire results and conclusions drawn from this study, and points out the recommendation for further research are presented in this study.
Chapter 1

INTRODUCTION

SOLID WASTE MANAGEMENT AND LANDFILL TECHNOLOGIES

Chapter 2

Landfill Technologies

Landfill Cover System

EVALUATION OF SOIL-FIBER MIXTURES AS A MATERIAL FOR COVER BARRIER LAYER

INVESTIGATION ON DESICCATION CRACK BEHAVIOR OF SOIL-FIBER MIXTURES

Compaction characteristics

Shear strength, Tensile strength

Hydraulic conductivity

Volumetric shrinkage strain

Variation in CIF

Crack depth prediction

Chapter 3

DESIGN CRITERIA OF SOIL-FIBER MIXTURES AS A MATERIAL FOR LANDFILL COVER BARRIER SYSTEM

Acceptable zone to meet all design criteria

Chapter 4

DESIGN AND PERFORMANCE OF MULTI-LAYER COVER BARRIER LAYER

Water balance analysis

Water interception performance and water storage capacity

Unsaturated hydraulic conductivity

Chapter 5

Chapter 6

Chapter 7

CONCLUSIONS AND RECOMMENDATION

Figure 1.1  Content and structure of this dissertation
References


2.1 General

The safe and reliable long-term disposal of solid waste residues is an important component of integrated waste management. Solid waste residues are waste components that are not recycled, that remain after processing at a materials recovery facility, or that remain after recovery of conversion products or energy. Historically, solid waste has been placed in the soil in the earth’s surface or deposited in the oceans. It is now argued that many of wastes now placed in landfill or on land could be used as fertilizers to increase productivity of the ocean or the land. Nevertheless, landfilling or land disposal is today the most commonly used method for waste disposal.

The sanitary landfill represented a dramatic improvement over the open dump. An engineering landfill is a controlled method of waste disposal. The most important requirement of a landfill is that it does not pollute or degrade its environment. Controlled placement of waste in sanitary landfills greatly reduced the number of rodents and insects, dramatically reduced public health risks, and generally contributed to major aesthetic improvements in waste disposal. Design of various landfills component and the development of landfill technologies will be briefly reviewed here.
2.2 The Development of Solid Waste Management

2.2.1 Historical Development

The most commonly recognized methods for the final disposal of solid wastes at the turn of the century were (1) dumping on land, (2) dumping in water, (3) plowing into the soil, (4) feeding the hogs, (5) reduction, and (6) incineration (Hering and Greely, 1921; Parson, 1906). Enlightened solid waste management, with emphasis on controlled tipping (not known as sanitary landfilling), began in early 1940’s in the United States and a decade earlier in the United Kingdom. During World War II, the U.S. Army Corps of Engineers modernized its solid waste disposal programs to serve as model landfills for communities of all sizes (Tchobanoglous et al., 1993).

The changes in regulation for waste disposal in Japan are presented in Table 2.1. Before the 1960s in Japan, the disposal of waste was dependent on anaerobic landfill, which merely abandons the waste to the depression in the ground and to the place of shallow water along the coastal without any cover soil or leachate treatment facility. The Technical Standard for Landfill Sites amended in year 1998 announced the clear standards for bottom liner systems as well as comprehensive regulations of landfill structure (Inazumi, 2003).

<table>
<thead>
<tr>
<th>Year</th>
<th>Laws and Regulation</th>
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<tbody>
<tr>
<td>1900</td>
<td>Filth cleansing law</td>
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<tr>
<td>1954</td>
<td>Public cleansing law</td>
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<tr>
<td>1970</td>
<td>Waste disposal law</td>
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<tr>
<td>1976</td>
<td>Revision of waste disposal law</td>
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<tr>
<td>1977</td>
<td>Technical standard for landfill sites</td>
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<td>1979</td>
<td>Guideline for landfill site</td>
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<td>1988</td>
<td>Amendment to guideline for landfill site</td>
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<td>Amendment to waste disposal law</td>
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<td>1997</td>
<td>Amendment to waste disposal law</td>
</tr>
<tr>
<td>1998</td>
<td>Amendment to technical standard for landfill site</td>
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</table>
2.2.2 Definition and Classification of Wastes

Waste is defined as any materials of solid, liquid, gas, or vapor, those are not used anymore in the production of commercial product or the provision of a service, those are not intended commercial product, and those are unwanted, unusable, and surplus. Wastes are thus regarded as the by-product or end products of the production and consumption process, respectively.

In Japan, wastes are classified into two categories, under the “Waste Disposal and Cleansing Act” (i.e., “Waste Disposal Law”) as a municipal solid waste (MSW) and an industrial waste, as shown in Figure 2.1 which shows the classification of waste under households and wastes similar character from shops, markets, offices, open areas, and treatment plant sites, respectively. The solid wastes generated by household are legally designated as a municipal solid waste and also the municipal solid waste also includes wastes from offices and enterprises, but not wastes generated during industrial production processes. The local governments in Japan typically manage the municipal solid waste. In the United States and European countries, the term “municipal solid waste” does not include waste generated by enterprises; and each enterprise is responsible for the cost of treating and disposing of all types of waste generated by their operations (Yasuda, 1997). A very wide range of wastes and actual composition of industrial wastes depend on the property of the industrial base. The industrial wastes may produce as relatively pure substances or as complex mixtures of varying composition and in varying physicochemical states. The examples of the industrial waste are excavated soil, slurry, or sludge by the construction industry, general factory rubbish, organic wastes from food processing, acids, alkalis, and tarry residues as shown in Figure 2.1. The most important feature of industrial waste is that significant proportion is regarded as hazardous or potentially toxic, thus requiring special handling, treatment, and disposal.

In Japan, the municipalities have the responsibility for the management of the disposal of municipal wastes. The disposal of industrial wastes is the responsibility of the organizations which generated the wastes. Due to this reason, the treatment facilities used for treat and discharge the industrial waste which involving the private waste disposal companies and public sector (Inazumi, 2003).
2.2.3 Elements of Waste Management System

Recently, the problems associated with the management of solid waste in society are complex because of the quantity and diverse nature of the waste, the development of sprawling urban areas, the funding limitations for public service in many large cities, the impact of technology, and the emerging limitations in both energy and raw materials. As a consequence, if solid waste management is to be accomplished in an efficient and orderly manner, the fundamental aspects and relationship involved must be identified, adjusted for uniformity of data, and understood clearly.

In this section, the activities associated with the management of solid wastes from the point of generation to final disposal have been grouped into the six functional elements: (1) waste generation, (2) waste handling and separation, storage, and processing at the waste, (3) Collection, (4) separation and processing, (5) transfer and transport, and (6)
disposal (Tchobanoglous et al., 1993). The functional elements are shown in Figure 2.2.

Waste generation encompasses activities in which materials are identified as no longer being value and are either thrown away or gathered together for disposal. Waste generation is, at present, an activity that is not very controllable. In the future, however, more control will be exercised over the generation of wastes. In United States where waste diversion goals are set by law, and must be met under threat of economic penalty, it is necessary to put in place a manifest system to monitor waste diversion. Source reduction, although not controlled by solid waste managers, is now included in system evaluations as a method of limiting the quantity of waste generated.

Waste handling and separation, storage, and processing at the source involve the activities associated with management of wastes until they are placed in storage containers for collection. Handling also encompasses the movement of loaded containers to the point of collection. Separation of waste components is an important step in the handling and storage of solid waste at the source.

Collection includes not only the gathering of solid wastes and recyclable materials, but also the transport of these materials, after collection, to the location where the collection vehicle is emptied. This location could be material processing facility, a transfer station, or a landfill disposal site. In small cities, where final disposal sites are nearby, the hauling of wastes is not a serious problem. In large cities, however, where the haul distance to the point of disposal is often very far. If a long distance is involved, transfer and transport facilities are normally used.

Separation, processing, and transformation of solid waste that occurs primarily in locations away from the source of waste generation are encompassed by this functional element. The separation and processing of wastes that have been separated at the source and the separation of commingled wastes usually occur at materials recovery facilities, transfer stations, combustion facilities, and disposal sites. Transformation processes are used to reduce the volume and weight of waste requiring disposal and to recover conversion products and energy. The most commonly used chemical transformation
process is combustion, which is used in conjunction with the recovery of energy in the form of heat.

*Transfer and transport* involves two steps: (1) the transfer of wastes from the smaller collection vehicle to the larger transport equipment and (2) the subsequent transport of the wastes, usually over long distances, to a processing or disposal site. The transfer usually takes places at a transfer station. Although motor vehicle transport is most common, rail cars and barges are also used to transport wastes.

*Disposal* is the final functional element in the solid waste management system. Recently the disposal of wastes by landfilling or landspreading is the ultimate fate of all solid wastes, whether they are residential wastes collected and transported directly to a landfill site, residual materials from recovery facilities, residue from the combustion of solid waste, compost, or other substance from various solid waste-processing facilities.

Figure 2.2  Simplified diagram showing the interrelationship between the functional element in a solid waste management system
2.3 Final Landfill Cover Technologies

Landfill cover systems are divided into final cover systems and daily cover systems. Final cover systems are designed as an impermeable cap on the top of landfill after the closure of landfill operations. A final cover system should semi-permanently prevent the infiltration of rainwater into the underlying waste layer, while a daily cover system should suppress the infiltration of rainwater into the waste layer during the waste reclamation stage. The primary purpose of final landfill cover systems are: (1) to minimize the infiltration of rainwater and melted snow into the landfill after the landfill has been completed, (2) to limit the uncontrolled release of landfill gases, (3) to suppress the proliferation of vectors, (4) to limit the potential for fire, (5) to provide a suitable surface for vegetation at the site, and (6) to serve as the central element in the reclamation at the site. To attain these goals, landfill final cover systems must be able to: (1) withstand climatic extremes (e.g., hot/cold, wet/dry and freeze/thaw), (2) resist water and erosion, (3) maintain stability against slumping, cracking, slope failure, and downward slippage or creep, (4) resist differential landfill settlement caused by the release of landfill gas and the compression of waste and foundation soil, (5) resist deformation caused by earthquakes, and (6) resist disruptions caused by plants, burrowing animals, worms, and insects (Hatheway and McAney, 1987; Koerner and Daniel, 1997; Tchobanologlous et al., 1993). It is important that legislation should exist which corresponds to attaining these above-mentioned goals and that it must continue to be updated in the future as necessary.

Furthermore, the daily cover systems are used to cover the waste which is discarded each day in order to eliminate the harboring of disease vectors, odor, to enhance the aesthetic appearance of landfill sites, and to limit the quantity of surface infiltration (Tchobanologlous et al., 1993). The daily cover systems also serve to resist failure due to landfilling operations such as surcharge loads brought about by stockpiling and the driving of collection vehicles across completed portions of the landfill. Some of the water, in the form of rain or snow, enters while the waste is being placed in the landfill. However, the placement of daily cover system can limit the quantity of surface water that infiltrates to a landfill. Although daily and final cover systems are somewhat structurally different, the goal of preventing the infiltration of water into the underlying waste layer is the same (Inazumi, 2003).
Figure 2.3 shows the schematic diagram of a municipal solid waste landfill containment system. The United States Environmental Protection Agency (EPA) and the various states have detailed regulations governing landfill siting, design construction, operation, groundwater and gas monitoring, landscaping plan, closure monitoring, and maintenance for 30 years. The situation commands worldwide interest and attention in that some 28 countries have regulation of either prescriptive of performance nature (Koerner and Koerner, 1999).

Final landfill covers (sometimes called caps) are the focus of this discussion. They are placed during remediation and remain in place as an essential part of the waste containment system. Over the past several decades, technologies have developed and advanced to enable the effective covering of landfills in accordance with environmental goals. At the same time, the process has become an expensive proposition and one largely driven by regulation. Ironically, regulations are sometimes blindly followed to the neglect of innovative technologies that can provide an environmentally responsible solution at considerable cost savings.
In the waste management of Japan, landfills are clarified, under the amendment of Technical Standard for Landfill Sites include least-controlled, controlled, or strictly controlled as shown in Figure 2.4. Isolated landfills are used for the disposal of hazardous industrial wastes. Leachate-controlled landfills are used to dispose of both municipal wastes and industrial wastes other than hazardous and stable wastes. The non leachate-controlled landfills are used to dispose of stable wastes, namely, waste plastics, rubber scrap, metal scrap, waste glass, and ceramics and demolition waste. The standards for landfill site structure and those for landfill site operation and maintenance have been developed in accordance with landfill type (Inazumi, 2003).

The landfill site structure, especially in the leachate-controlled landfill structure, indicates that a cover system is not required as one of the waste containment facilities in Japan. This is because an aerobic and a semi-aerobic landfilling prevails in Japan, where landfill sites are expected to become stable enough for land utilization in a short time after landfill completion (Hanashima and Furuichi, 2000). The philosophy of the semi-aerobic landfilling method is to allow as much infiltration as would practically occur. This would bring the landfill to field capacity quickly and allow the removal of large proportion of contaminants by the leachate collection system. Much infiltration is helpful to maintain an aerobic respiration within landfill, speeding up the decomposition of organic materials. The disadvantages of this approach are: (1) larger volumes of leachate must be treated, (2) if the leachate collection system fails (e.g. clogging of the drainage pipe), a high infiltration will result in significant leachate mounding, and (3) the complete biodegradation of organic waste cannot be expected, especially in recent years that waste at landfill sites has been changed to incinerator ash from the organic raw waste (Inazumi, 2003).

There are various philosophies to approach the design and management of a landfill as reported by Rowe et al. (1995), among which the role of cover system should be noted. One is to provide a cover system as impermeable as soon as possible after the landfill has ceased operating, so as to minimize the generation of leachate. This approach has the benefits of minimizing both amount of leachate that must be collected and treated, and the mounding of leachate within the landfill. Anaerobic decomposition due to installation of the cover system provides a reducing condition within the landfills, which is favorable to
the fixation of heavy metals, tending to decrease the pollution risk of leachate to the nearby environment. It also has the disadvantage of extending the contaminating lifespan. With low infiltration, it may take decades to centuries before the field capacity of waste is reached and full leachate generation to occur.

Figure 2.4   Types of waste containment in Japan
(adopted from Inazumi, 2003)
There are fundamental scientific and technical reasons for placing a cover on a landfill site. Although regulation appear to drive the selection and design of landfill covers nowadays, these regulations originated from specific environmental concerns and have a technical basis. Landfill covers offer many environmental benefits, but there are three preeminent objectives in their application include minimizing infiltration, isolating waste, controlling landfill gasses. These three principal goals are common to all landfill cover designs. The way in which they are technically implemented can be quite different. Landfill covers are inherently intended to remain in place and provide protection to the environment for an extended period, perhaps century. However, most commonly used cover technologies have only been in existence for about 20 years. It is not known exactly how landfill cover performance will change over time. Innovative covers that do not rely on an impermeable barrier may offer more reliability in this respect (AFCEE/ERT, 1999).

2.3.1 Site-Specific Aspects of Landfill Cover Selection and Design

Since the purpose of landfill cover are clear, the particular implementation as translated into design elements is dependent on specific site characteristics. The site characteristics that have a dominant influence on choosing an appropriate final cover include climate, soils, landfill characteristics, hydrogeology, gas production, seismic environment, and reuse of landfill areas (AFCEE/ERT, 1999).

Climate

Precipitation (rain, snow), solar radiation, temperature, and wind are the main climatic factors that affect landfill covers. Precipitation amount and intensity, of course, have a direct bearing on infiltration of water into the cover and, potentially, into the buried waste. Climatic factors also strongly influence evapotranspiration, which acts to reduce infiltration into the waste. Degradation rates of biodegradable wastes will be affected by climatic variables through effects on moisture content and temperature. Soil erosion is directly affected by rainfall intensity and wind. Beyond macro-climatic effects, there is also strong influence of daily or even hourly patterns of the precipitation. A series of precipitation events that saturate the soil will lead to greater infiltration that same total amount of precipitation spread over a longer time period. The antecedent moisture
condition is just one factor that illustrates the complexity of climatic interactions that have to be considered in evaluating potential landfill covers. In addition to the general conditions, the concept of a critical event has to be taken into account. An example of such a critical event would be an extended period of rain following snowmelt that coincides with a period when vegetation is dormant and may occur only rarely.

**Soils**

The availability of appropriate local soils is an important consideration in any landfill design, as it is often needed for a compacted barrier layer. Major factors determining effectiveness of the soil for supporting vegetation are grain size, soil pH, and cation exchange capacity. An adequate supply of nutrients to support vigorous plant growth is also required but can be achieved by using soil amendments. Although soil could be classified by visual inspection, the determination of soil type and soil properties should be based on appropriate soil testing. Generally, loam soils provide excellent cover for landfills. Soils made up largely of sand tend to dry out rapidly because they have low water holding capacity and they lose nutrients by leaching. Differences in soil type also influence the selections of vegetation and mulch. A landfill cover that relies on a conventional barrier system often incorporates a compacted clay layer (CCL) into the design. The availability of local soil that has the necessary properties to compose this layer is critical cost factor in selecting the appropriate design particular, is important, and the cover will not be practical unless sufficient soils with the appropriate characteristics are available near the site.

**Landfill Characteristics**

Some of the characteristics that affect cover design include the type of waste deposited whether or not the landfill has a liner, the age of the landfill, whether the landfill is active or inactive, and whether or not leachate is being produced. The type of wastes disposed in a landfill leads to its classification as municipal or sanitary, hazardous, radioactive, or mixed waste. The waste classification directly impacts the cover design because of both the technical and the regulatory requirements. The physical form of the waste and its chemical properties are an important consideration in selecting materials for the cover. If the buried waste is biodegradable, production of landfill gas can be anticipated and gas
collection must be considered when designing the cover. As a landfill ages, the degradation of the waste and the pressure of overlying materials leads to setting of the waste, sometimes by as much as 33 percent (Suter et al., 1993). The resulting subsidence of the overlying cover can cause severe problems, including separation of geomembranes (GMs), development of cracks in clay barriers, and slope changes that adversely affect water flow and retention. Although gas production in a landfill can continue for long periods, high rates occur over relatively short periods—perhaps up to ten years. Hauser and Weand (1998) found that 79 percent of Air Force landfills have been dormant for more than 20 years.

**Hydrogeology**

The distance between the bottom of an unlined landfill and the water table is an important determinant of the probability that groundwater has been or may be contaminated. If the landfill has no liner but rests on highly impermeable bedrock, shale, or clay, and if the depth to groundwater is great, then an old landfill poses little threat to groundwater. Therefore, the geology of the site (especially the lithology between the waste and permanent groundwater) is an important consideration. If waste is actually in contact with groundwater, a cover alone cannot provide a complete remedial solution for the site. A landfill cover at such a site should be selected with extra care and integrated with other remediation technologies being employed.

**Gas Production**

Gas production must be considered in the overall cover design. Natural decay of wastes and volatilization of wastes in landfills may produce sufficient toxic and/or explosive landfill gas to warrant gas control systems under the cover. Gas control systems may be either passive (natural flow) or active (using pumps). A cover that employs a conventional barrier layer likely to require an expensive gas control system because their barrier is likely to trap gas produced at even low rates to yield dangerous volumes of explosive and/or poisonous gas. Some innovative covers, such as the ET cover, contain no barriers and may allow small amounts of landfill gas to pass harmlessly into the atmosphere.
Seismic Environment

Earthquakes are a significant threat to public safety and welfare over many parts of the United States. The ground shaking associated with earthquake activity can damage landfill structure in many ways, including landslides on the cover, rupture of barrier layers, breakage of conduit lines, and change in drainage slopes. Within seismic hazard zones, landfill design should be evaluated using site-specific seismic risk assessment criteria. Richardson and Kavazanjian (1995) have written extensive treatment of this aspect of landfill design.

Reuse of Landfill Areas

Land reuse is an important consideration in landfill cover selection and design. Former landfills sites find new life as parks, golf courses, nature areas, and sport paths. The anticipated use will require using compatible materials in the cover, perhaps modifying the topography, and selecting vegetation that not only provides the necessary cover functions but is also appropriate for the end use.

There are various philosophies to approach the design and management of a landfill as pointed out by Rowe et al. (1995), among which the role of cover system should be note. In the United States and most European countries, it has already been recognized that the installation of cover system as a landfill containment facilities is an effective method of water interception for the prevention of the generation of leachate. According to the recommended criteria of the USEPA, the thickness of the constituent layers of final cover systems and the standard for the hydraulic conductivity of the barrier layers are considered to the Subtitle D of Resource Conversation and Recovery Act (RCRA). However, Japan is a country where there is no governmental requirement to design a modern cover system with low hydraulic conductivity in landfills.

2.3.2 Component of Final cover system

Covers placed over landfills are multicomponent cover systems that are constructed directly on top of the waste shortly after a specific unit or cell has been filled to capacity.
A typical design and material used of final cover system is illustrated in Figure 2.5. The common components within a final cover system are the erosion control layer, protection layer, drainage layer, hydraulic barrier layer, gas vent layer, and foundation layer. Not all components are needed for all final covers. For example a gas vent layer may be required for some covers but not others, depending upon whether the waste is producing gases that require collection and management. In addition, some of the layers may be combined. The gas collection layer can be combined as a single layer with the foundation layer (Daniel, 1995; Koerner and Daniel, 1997).

The construction criteria and the evaluation techniques for landfill cover systems have already been established by many investigators (Daniel, 1995; Daniel and Koerner, 1995). In the united States, the EPA distributes the minimum criteria for the construction of final cover systems based on Subtitle D of resource Conversation and recovery Act (RCRA) in
year 1992. According to the recommended construction criteria of the USEPA (1995), the thickness of the constituent layers of final cover systems and the standards for the hydraulic conductivity of barrier layers are recommended and are considered as shown in Fig. 2.6. Daniel and Koerner (1995) reported that the hydraulic conductivity of a barrier layer in a cover system for a municipal solid waste (MSW) landfill has been determined at lower than or equal to $1 \times 10^{-5}$ cm/s. In addition, a barrier layer, which has a level of hydraulic conductivity lower than $1 \times 10^{-7}$ cm/s can perform excellently for all types of landfills. In general, it can be expected that final cover system and bottom liner systems have similar levels of hydraulic conductivity (Parker et al., 1993).

![Typical cross section of final cover system for municipal solid waste landfill](image)

Japan is a country where there is no governmental requirement to design a modern cover system with low hydraulic conductivity in landfills. Therefore, the present study evaluates the performance of innovative hydraulic barrier layer in reducing greatly the rainwater infiltration into landfills and so as to decrease the pollution risk by leachate generation to the nearby environment.
2.3.3. Hydraulic Barrier Cover System

The barrier layer (often called “hydraulic” barrier) is generally viewed as the most critical component of a cover system. The barrier layer minimizes percolation of water through the cover system directly by blocking water and indirectly by promoting storage of drainage of water in the overlying layers, where water is eventually removed by runoff, evapotranspiration, or internal drainage. Furthermore, the barrier layer prevents landfill gases from escaping into the atmosphere. Such gases have been shown to be major source of air pollution and ozone depletion. Components of a typical hydraulic barrier type cover system are briefly introduced. The usual sequencing of these typical components is illustrated in Figure 2.5.

Surface Layer

The primary functions of the surface layer are to resist erosion by water and wind, be maintainable and, depending on the situation, provide a growing medium for vegetation and satisfy project aesthetic, ecological and post-closure land-use criteria. Material that may be used for final cover system surface layers include: (a) topsoil, (b) amended topsoil, (c) lightweight soil, (d) rip-rap, (e) gravel-soil mixture, (f) asphaltic concrete, and (g) other materials. Of these materials, topsoil is, by far, the one most commonly used. Suitable topsoil will promote growth of vegetation, thereby maximizing the evapotranspirative component of the cover system water balance. Vegetation also decrease stormwater run-off velocities from cover system slopes and reinforces the topsoil; both of these effects reduce the rate of erosion of topsoil in comparison to a topsoil layer with out vegetation. In areas where the amount of precipitation is inadequate to support growth of a vegetation layer, riprap, gravel-soil mixtures, asphaltic concrete, or other materials may be used for the surface layer.

Protection Layer

A protection layer may serve several function (Daniel & Koerner 1993b): (a) store water that has infiltrated through the surface layer until the water later returns to the atmosphere through evapotranspiration; (b) serve as a barrier to human, burrowing animal, or plant
root intrusion; (c) protect underlying layers from wet-dry cycles, which could cause cracking of some materials; (d) protect underlying layers from freezing, which could also cause cracking of some materials; and (e) restrict emissions of radon gas for those wastes, such as uranium mill tailings, the emit radon. On site or locally available soil is usually suitable for protection layer construction if the primary function of the layer is to serve as a vegetation root zone or for freeze-thaw protection. However, if the primary role of the protection layer is to prevent intrusion by burrowing animals, cobbles, asphaltic concrete or similar materials will typically be required.

**Internal Drainage Layer**

In a hydraulic-barrier type cover system, an internal drainage layer may be required above the hydraulic barrier. The functions of this drainage layer are: (a) to limit the buildup of hydraulic head on the underlying barrier layer, which minimizes percolation of water through the barrier; (b) to drain the overlying protection and surface layers, which increase the available water storage capacity of these layers and helps to minimizes erosion of these layers by reducing the time during which the surface and protection layer materials remain saturated with water; and (c) to prevent excessive seepage forces in surface, protection, and drainage layer materials, which improves cover system slope stability. Materials used for drainage layers include sand, gravel, geonets and geocomposite drainage materials. The material used must have adequate hydraulic conductivity to prevent a buildup of liquid head in the slope and adequate hydraulic transmissivity to laterally convey the design flow rate. Geotextile filter layers are typically used to achieve this function, although soil filter layers can also be used. If the drainage layer consist of gravel and the underlying barrier layer is a geomembrane, a geotextile cushion layer will typically be needed between the geomembrane and gravel. One of the most important aspects of designing an internal drainage layer is providing for free drainage at the layer discharge point.

**Hydraulic Barrier layer**

The function of a hydraulic barrier layer is to minimize percolation of water through the cover system. Properly designed barrier layers can virtually eliminate infiltration into
waste. Hydraulic barrier layer also restrict migration of gas or volatile constituents from the waste to the atmosphere. Materials used for barrier layer construction include CCLs, GCLs and geomembranes. These barrier materials may be used alone or in combination. Historically, CCLs were the most frequently used barrier layer material. Procedures for initial construction of CCL barriers to meet permeability criteria are well established. However, when used alone, CCLs barriers in cover system may not maintain low permeability in the long term. USEPA (1999) describes a number of field case studies where CCL barriers exhibited increasing permeability with time when used alone as waste covers even when overlain by protection and surface layers. This increase is attributed to desiccation cracking, wet-dry and freeze-thaw effects, root penetration, and differential settlement. Field studies by Montgomery & Parsons (1989); Corser & Cranston (1991); Melchior (1997); and the Maine Bureau of remediation and Waste management (1997) demonstrate the problem. The USEPA suggests that the best way (USEPA 1999) to maintain low CCL permeability in cover application is to overlay the CCL with both a geomembrane and an adequate thickness of protection soil. Furthermore, the GCLs are factory fabricated products having attractive features for cover system applications, which include very low saturated hydraulic conductivity (e.g. \( k \leq 5 \times 10^{-11} \) m/s), preservation of low hydraulic conductivity when subjected to differential settlement, and ease of installation. Disadvantages include low hydrated shear strength, potential for increased hydraulic conductivity due to cation exchange reactions under certain conditions, and potential for premature hydration during installation. GCLs are increasingly being used in cover system applications. The results of a large-scale test plot program sponsored by the USEPA to evaluate GCL use in cover system are reported in Daniel & Scranton (1996) and Daniel et al. (1998). Moreover, Geomembranes are factory-manufactured polymeric materials that are widely used as hydraulic barriers in cover systems due to their non-porous structure, flexibility, and ease of installation. Spray-on elastomeric and bituminous membranes are also available, but are rarely used in cover system applications.

**Gas Transmission Layer**

Gas transmission layers may be necessary beneath cover system barrier layers for wastes that generate gas. These layers are designed to have adequate in-plane gas transmissivity to convey gas to passive gas vents, active gas wells, or trenches. Gas transmission layers
are typically a necessary complement to systems that utilize passive gas vents. Gas transmission layers may not always be needed for landfills with active gas extraction systems, depending on gas generation rates in the landfill, extraction well spacing, presence or absence of horizontal gas trenches, and other factors. Gas transmission layers may be constructed of granular materials or geosynthetics (geotextiles, geonet or geocomposites). When a granular material is used, a separation layer (typically a geotextile) may be needed to separate the granular material from the overlying barrier layer.

*Foundation Layer*

The foundation layer forms the bottom-most component of the cover system. The functions of the foundation layer are to provide grade control for cover system construction, adequate bearing capacity for overlying layers, firm subgrade for compaction of overlying layers, smooth surface for installation of overlying geosynthetics, and, in some applications, buffer zone to reduce the potential effects of waste differential settlements on cover system components. Material most often used for foundation layer include on site or locally available soils. Sometimes, intermediate cover soil already in place is used for all or a portion of the foundation layer. In a few situations, waste material can be used to construct the foundation layer. If constructed of granular material, the foundation layer may also serve as a gas transmission layer.

In the United States, many regulatory agencies have traditionally required a low hydraulic conductivity, compacted soil liner (or the equivalent) as primary hydraulic barrier layer within landfill cover systems. Table 2.2 presents the advantages and disadvantages of the three barrier materials. Environmental stresses such as freeze-thaw, wet-dry, and distortion caused by differential settlement are much more damaging to low hydraulic conductivity compacted soil liners than to geomembranes and GCLs. On the other hand, the interfacial shear strength between a geomembrane, GCLs, and the adjacent material may limit the steepness of side slopes on which geomembrane and GCLs could be used. Also, thin barrier layers such as geomembrane and GCLs are more vulnerable to construction damage or post construction puncture, although the consequences of an occasional, unanticipated puncture are much less severe in a cover system than a bottom liner system.
Regulators and design engineers should weigh the advantages and disadvantages of the alternative materials and then select the suitable material depending on the specific requirements of individual projects. Recently, there is an increasing interest in the use of additive materials as a material for landfill cover barrier layer. Some researcher reported the utilization of fiber reinforcement increased the geotechnical properties of waste containment soil liners (Miller and Rifai, 2004).

Table 2.2 Principal advantages and disadvantages of barrier materials (adopted from Daniel, 1995)

<table>
<thead>
<tr>
<th>Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Compacted soil with low hydraulic conductivity | 1. Long history of use  
2. Regulatory approval is virtually assured  
3. Large thickness ensures that layer will not be breached by puncture  
4. Large thickness provides physical separation between waste and surface environment  
5. Cost is low if material is locally available | 1. Soil can dessicate and crack  
2. Liner must be protected from freezing  
3. Low resistance to cracking from differential settlement  
4. Difficult to compact soil above compressible waste  
5. Suitable soils net always locally available  
6. Difficult to repair if damaged  
7. Slow construction |
| Geomembrane                            | 1. Rapid installation  
2. Virtually impermeable to water if properly installed  
3. Low cost  
4. Not vulnerable to desiccation or freeze-thaw damage  
5. Can withstand large tensile strain  
6. Low weight and volume consumed by liner  
7. Easy to repair | 1. Potential strength problem at interface with other materials  
2. Geomembranes can be punctured during or after installation |
| Geosynthetic Clay Liners                | 1. Rapid installation  
2. Very low hydraulic conductivity to water if properly installed  
3. Low cost  
4. Excellent resistance to freeze-thaw damage  
5. Can withstand large differential settlement  
6. Not dependent on availability of local soil  
7. Low weight and volume consumed by liner  
8. Easy to repair | 1. Low shear strength of hydrated bentonite  
2. GCLs can be punctured during or after installation  
3. Dry bentonite (e.g. at time of installation) is not impermeable to gas  
4. Potential strength problems at interface with other materials |
References


Chapter 3

EVALUATION OF SOIL-FIBER MIXTURES AS A MATERIAL FOR COVER BARRIER LAYER

3.1 General

The compacted cohesive soil (clay, silt) are generally used as a material for cover barrier layer. The capping system with mineral liners such as compacted clay liners (CCL) and geosynthetics clay liners (GCL) are applied as a standard cover for landfills with small or medium hazardous waste. During dry period, the clay layers can show a suction-induced dewatering due to seasonal fluctuation of the layer soil moisture. If an ultimate suction is exceeded in the clay liner, irreversible cracks will occur and will reduce the sealing effect dramatically and will cause decreasing in the service time of the landfill cover system.

In order to study the potential future uses of the landfill site for other applications (i.e. residential, park, sports fields, etc.), some of the geotechnical properties need to be investigated when the landfill cover is used as a bearing layer during the post-closure period. Since the compacted clay liner (CCL) soil have been widely used as a barrier system material to cover waste disposal sites for many years, their performance on the engineering properties have long been questioned such as the CCL must be as ductile as possible to accommodate differential settlement and must be resistant to cracking from moisture variation (i.e. desiccation). Moreover, the landfill covers are generally constructed with a slope to maximize waste volume and to promote runoff, the slope stability problem also encountered in the landfill cover system. Therefore, to satisfy the
functional requirement, analysis and design methods have been developed by some researcher to evaluate the performance of the material used alone or in combination of soil mixtures.

In this chapter, the investigation was made to evaluate the using of polypropylene fiber \((C_3H_6)\) additives on the compacted Akaboku soil potentially used as a material for landfill cover barrier layer. The laboratory tests were performed to investigate the effects of fiber additives on the geotechnical properties of compacted Akaboku soils. The x-ray diffraction (XRD) was also conducted in order to study the mineral composition of the soil used in this study. Moreover, the parameters for the design of cover barrier layer such as compaction characteristic, unconfined compressive strength, cohesion, internal friction angle, tensile strength and hydraulic conductivity were investigated to evaluate the suitability of the soil-fiber mixture being used as a material for landfill cover barrier system for future uses during the post-closure period of landfill. The effect of the fiber content on the geotechnical properties of the compacted Akaboku soil was discussed.

### 3.2 Utilization of Fiber as Reinforcement Material

The concept of reinforcing soil masses by including some kind of fiber was practice by early civilizations which used soil mixed with available fiber to improve the mechanical properties of building materials. They found that fibrous soil works better than natural soil. Early developments in soil fiber composites were in the area of reinforced earth. Vidal (1978) conducted studies on utilization of galvanized steel for reinforcing retaining wall backfill. Furthermore, in landfill cover systems, the barrier layer has designed over the years using natural material or a combination of natural and synthetic materials.

Moreover, the inclusion of fibers in soil specimens is expected to increase the soil strength and improve the stability if it is used as a bearing layer. Some researchers were conducted research by use randomly oriented discrete geosynthetic fiber to reinforced sand, such as Gray and Ohashi (1983), Park and Tan (2005) and Latha and Murthy (2007). Other study indicated that the compacted rubber fiber-clay was used to increase the shear strength of the composite soil (Ozkul and Baykal, 2007). Nataraj and McManis (1997) studied the strength and deformation characteristics of soil reinforced with randomly distributed fibers.
compared to natural soil. Tang et al. (2007) concluded that using fiber as reinforcement is advantageous attributed to increase in the strength, decrease in the stiffness and decrease in brittleness of soil-cement. Ziegler et al. (1998) found that with an inclusion of discrete polypropylene fibers, the tensile strength of clays tend to increase and induce more ductile failures. The compaction path also significantly effected to the tensile strength (Ibarra et al., 2005). The polypropylene fibers have been found to increase the hydraulic conductivity of soil which is used as material for waste containment soil liners (Miller and Rifai, 2004). The study by Cai et al. (2006) reported that there is a significant improvement on the engineering properties of the fiber-lime treated soil. Very few studies on the use of soil-fiber mixture as a material for landfill cover barrier have been reported.

3.3 Experimental Procedures on Soil-Fiber Mixture as a Material for Cover Barrier Layer

3.3.1 Materials Used

The materials used in this study are volcanic soil (Akaboku) and polypropylene (C₃H₆) fiber. The volcanic soil (Akaboku) was locally sampled from Kumamoto Prefecture, Kyushu Island, Japan. The Akaboku soil was air dried prior to testing due to very high water content of 141.9%. The location of sample collected is shown in Figure 3.1.

Polypropylene fiber is the most common synthetic material used to reinforce soil and concrete (Maher and Ho 1994; Al Wahab and El-Kedrah 1995). The primary attraction is that of low cost (Moncrieff 1979). The polypropylene fiber (RCP17T) with 10mm length and 50 µm in diameter was used in this study. The polypropylene fiber is easy to mix with soil and has relatively high melting point which makes it possible to determine the water content of soil-fiber mixture without changing the physical properties. Also, polypropylene fiber is a hydrophobic and chemically inert material which does not absorb or react with the soil moisture or leachate. The properties of the polypropylene fiber are summarized in Table 3.1. Rate of elastic deformation is represented as the amount of elongation. Fiber fineness indicates the value of fiber embedment during compression and
mechanical composite properties. The photograph of the polypropylene fiber is shown in Figure 3.2, and determination of the diameter of the polypropylene fiber by using Scanning Electron Microscope (SEM) is shown in Figure 3.3.

Table 3.1 Properties of polypropylene fiber

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>0.91</td>
</tr>
<tr>
<td>Fineness (dtex)(^1)</td>
<td>15-19</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>2.0 - 6.0</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>70 - 150</td>
</tr>
<tr>
<td>Melt point ( °C)</td>
<td>160</td>
</tr>
</tbody>
</table>

\(^1\) dtex = 10µg/cm

Figure 3.1 Sample collected location (Kumamoto Prefecture, Kyushu Island)
Figure 3.2  Photograph of polypropylene fiber

Figure 3.3  Diameter determination of polypropylene fiber using SEM
3.3.2 X-Ray Diffraction Test

The X-ray diffraction (XRD) is the most widely used method for identification of fine-grained soil minerals and the study of their crystal structure. The X-ray diffractometer (RINT) was used to analyze the clay mineral composition of Akaboku soil. Since the clay mineral are characterized by first order basal reflection at 7, 10, or 14 Å, identification of specific mineral groups ordinarily requires specific pretreatments. Magnesium (MgCl₂), potassium (K) and glycerol are most frequently used for saturation the soil specimen. The Mg-saturated, K-saturated, and Glycerol-saturated specimens were saturated for 24 hours and followed by X-raying. Another K-saturated specimen was heated at 550°C and x-rayed. The basal spacing \( d \) was determined using the Bragg’s law by the following equation

\[
 n \lambda = 2d \sin \Theta
\]  

(3.1)

where \( n \) is the order reflection, \( \lambda \) is the wave length (1.54 Å), and \( \Theta \) is the deflection angle. The X-ray diffraction pattern of the soil specimen is shown in Figure 3.4.

![Figure 3.4 X-ray diffraction pattern of the glycerol solvated Akaboku soil](image)
3.3.3 Basic Properties Test

The basic properties of the Akaboku soil were determined according to standard practice ASTM Methods D422-63, D854-58, D4318-00, and D427-61. The summary of basic properties data are summarized in Table 3.2. The Unified Soil Classification System (USCS) was used for soil classification analysis. The Akaboku soil is classified as a fine-grained soil in terms of their consistency characteristics using the plasticity chart shown in Figure 3.5. Using the the plasticity chart (Fig. 3.5) the soil designation is Elastic Silt (MH).

Table 3.2 Physical properties of the Akaboku soil

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content (%)</td>
<td>141.9</td>
</tr>
<tr>
<td>Specific gravity, Gs</td>
<td>2.59</td>
</tr>
<tr>
<td>Consistency limit :</td>
<td></td>
</tr>
<tr>
<td>Liquid limit, $w_L$ (%)</td>
<td>162.0</td>
</tr>
<tr>
<td>Plastic limit, $w_P$ (%)</td>
<td>81.7</td>
</tr>
<tr>
<td>Shrinkage limit, $w_S$ (%)</td>
<td>48.9</td>
</tr>
<tr>
<td>Plasticity index, PI (%)</td>
<td>80.3</td>
</tr>
<tr>
<td>Grain size analysis :</td>
<td></td>
</tr>
<tr>
<td>Sand (%)</td>
<td>35</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>52</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 3.5 The plasticity chart in the classification of the soil
3.3.4 Soil-fiber Mixture Preparation

The water content of the Akaboku soil was found very high in natural condition. Therefore, the sampled soil was slight air dried to bring water content below the measured optimum moisture content (OMC). The air dried soils were grinded passed through a No. 10 sieves. The soil specimens were kept in box under room conditions (25 ± 2 °C, 50 ± 1 % relative humidity) prior to testing. Certain amount of distilled water was added to the soil specimen until the water content reach at OMC. The weight of specific content of fibers was calculated based on the weight of the soil (oven-dried basis). The soil and fiber were mixed for 5 minutes at low speed (1430 rpm) and additional 2.5 minutes at high speed (1720 rpm). Figure 3.6 showed the arrangement of Akaboku soil and fibers in the bowl for mixing. The mixing equipment which is used in this study is shown in Figure 3.7. The specimens were prepared by mixing the soil with various percentages of fiber content (FC) and the percentages of mixtures (by weight) presented in Table 3.3. Figure 3.8 showed the photograph of the soil-fiber mixture using a digital camera (Canon EOS, zoom lens EF 55-200 mm 1:4.5 – 5.6). It can be seen that the fibers are randomly distributed in the soil specimen and indicated that the mixing procedure used in this study is quite good.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>By weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natural soil (0.0 % Fiber)</td>
</tr>
<tr>
<td>2</td>
<td>0.2 % Fiber</td>
</tr>
<tr>
<td>3</td>
<td>0.4 % Fiber</td>
</tr>
<tr>
<td>4</td>
<td>0.6 % Fiber</td>
</tr>
<tr>
<td>5</td>
<td>0.8 % Fiber</td>
</tr>
<tr>
<td>6</td>
<td>1.0 % Fiber</td>
</tr>
<tr>
<td>7</td>
<td>1.2 % Fiber</td>
</tr>
</tbody>
</table>
Figure 3.6  Placement of Akaboku soil and fibers in a steel bowl for mixing

Figure 3.7  Mixing equipment (ES-DBF Type)
Figure 3.8  Photograph of soil-fiber mixture
3.3.5 Compaction Test

The standard Proctor compaction apparatus was used to compact the soil samples at various fiber contents according to ASTM D698-70. Compaction energy was equal to the compaction energy used in standard Proctor compaction tests, 593 kJm$^{-3}$. Compaction characteristics curves were determine for each fiber contents, such as 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2%. The result of this test provides information on the optimum moisture content (OMC) and maximum dry density ($\gamma_{d\text{ max}}$) of each fiber contents investigated.

3.3.6 Unconfined Compression Test

The unconfined compression test was used for obtaining the compressive strength of the soil samples and determined according to ASTM D2166-66. The soil samples were compacted at OMC and maximum dry density ($\gamma_{d\text{ max}}$) using a Harvard miniature compacter.

Using the stress-strain curves which is obtained in this test, the stiffness properties (i.e. the secant modulus) of the soil-fiber mixtures was evaluated. The secant modulus can be used to characterize the stiffness of soil and also can be used for the calculation of settlement in the practical application. The $E_{50}$ (secant modulus at 50% of the unconfined compressive strength ($q_u$)) was used as a parameter in determining the stiffness of the soil-fiber mixtures. The $E_{50}$ is determined as the slope of a tangent line at the origin point to the point of 50% maximum compressive stress in the stress-strain curve. The $E_{50}$ is calculated by the following equation:

$$E_{50} = \frac{q_u}{\varepsilon_{50}} \frac{2}{E_{50}} \quad (3.2)$$

where $q_u$ is the unconfined compressive strength and $\varepsilon_{50}$ is the strain which corresponding to the 50% of $q_u$. 

41
The energy absorption capacity (toughness index) was also determined in this study. The toughness index \((TI)\) can be expressed as the area under the normalized stress-strain curve from an initial state to a post-peak state in a specific stress level as shown in Figure 3.9. The \(TI\) can be determined by the following equation:

\[
TI = \int_0^{\varepsilon'_r} f(\varepsilon') \, d\varepsilon'
\]  

(3.3)

where \(\varepsilon'\) is the normalized strain \((\varepsilon / \varepsilon_f)\), \(\varepsilon_f\) is the strain at failure, \(f(\varepsilon')\) is the function of the normalized stress \((\sigma/q_u)\), and \(\varepsilon'_r\) is defined as the \(\varepsilon'\) at \(\sigma/q_u = r \) \((r < 1)\). In this study, \(r = 0.8\) was taken and \(\varepsilon'_r\) may be alternatively taken simply that is larger than \(\varepsilon_f\), i.e. \(\varepsilon'_r = 2 \varepsilon_f\) or \(3 \varepsilon_f\).

![Figure 3.9 Schematic normalized stress-strain curve for evaluation of TI](image-url)
3.3.7 Tensile Test

In order to observe the behavior of soil-fiber mixtures on the tensile force due to differential settlement, the tensile test was performed. The specimens were prepared cylindrical with 12.74 cm in height and 10 cm in diameter. The soil samples were compacted at OMC and $\gamma_{d,\text{max}}$ using a standard Proctor compacter. Also, the FC is the same as the tests mentioned in the previous section. Figure 3.10 shows the schematic diagram of the modified indirect tensile apparatus which is used in this study. The design of the apparatus for measuring soil tensile strength ($\sigma_T$) followed a principle similar to the device used for Brazilian test. The compression loading with a rate of 1 mm min$^{-1}$ was applied to the specimens until specimens failed. The tensile test was conducted by applying load along the soil thickness in between two flat parallel plates according to the indirect Brazilian test described by Dexter and Kroesbergen (1985). The $\sigma_T$ value was determined based on the following equation proposed by Frydman (1964).

$$\sigma_T = \frac{2F}{\pi dl} g(x)$$

(3.4)

where $F$ is the applied force, $d$ and $l$ represent specimen diameter and thickness. Frydman (1964) suggested a flattening coefficient $g(x)$ by the following relation:

$$g(x) = \left(-\frac{d}{2a}\right) \left\{2x - \sin 2x - \left(\frac{2}{d}\right) \ln \left(\frac{\pi}{4} + \frac{x}{2}\right)\right\}$$

(3.5)

where $x$ is the flattening ratio such that $x = a / y$, $a$ is the width of flattened portion, and $y$ is the vertical distance between the flattened portions at failure. The equation (3.5) may be applied if the value of $g(x)$ greater than 0.9. Otherwise, the $\sigma_T$ is calculated based on the following equation:

$$\sigma_T = \frac{2F}{\pi dl}$$

(3.6)
Figure 3.10  Schematic diagram of the modified indirect tensile apparatus

Figure 3.11  Determination the strain at peak value of tensile strength
In order to determine the strain at failure of tensile test ($\varepsilon_{fT}$), the photograph of the soil specimens were used. The photograph was taken using a digital camera (Canon EOS, zoom lens EF 55-200 mm 1:4.5 – 5.6) as shown in Figure 3.11. The $\varepsilon_{fT}$ was measured using a computer image pixel DataPicker ver.1.2. The $\varepsilon_{fT}$ is defined as the change in length ($\Delta L = L_f - L_0$) to the initial length of two points ($L_0$) with the following relation:

$$
\varepsilon_{fT} = \frac{\Delta L}{L_0}
$$  \hspace{1cm} (3.7)

where $L_I$ is the length between two points at failure.

### 3.3.8 Direct Shear Test

The direct shear test was carried out according to ASTM D 3080. The specimens for the shear tests were made in cylindrical mold with 2 cm in height and 6 cm in diameter by static compaction at the OMC and $\gamma_{d\ max}$. The normal pressures ($\sigma_1$) of 50, 100, 200 kPa were applied to the soil-fiber mixtures in order to define the shear strength parameters ($c$ and $\phi$). The total stress was obtained in this study.

### 3.3.9 Hydraulic Conductivity Test

In order to evaluate the permeability of soil-fiber mixtures, the hydraulic conductivity test was conducted in this study. Similar to the tensile test, soil samples were also prepared at OMC and $\gamma_{d\ max}$ using a standard Proctor compacter. The compacted soil specimen was placed in a flexible-wall permeameter for hydraulic conductivity test in accordance with ASTM D2434-68. The schematic diagram of hydraulic conductivity test is shown in Figure 3.12. The specimens were prepared cylindrical in 12.74 cm in height and 10 cm in diameter. The fiber content is the same as in the test that previously mentioned above. For all specimens, the hydraulic gradient ($i$) was set to 24 and confining stress of 60 kPa was applied. The hydraulic conductivity test that was performed at low confining stress for barrier materials provides the most practical approach to simulate the worst condition (Moo-Young and Zimmie, 1996a; Inazumi, 2003).
Figure 3.12  Schematic diagram of flexible-wall hydraulic conductivity test setup
3.4 Test Results and Discussions

3.4.1 Compaction Characteristics

From Figure 3.13, it can be seen that the addition of fibers affected both the $\gamma_{d\text{max}}$ and OMC. The $\gamma_{d\text{max}}$ of soil-fiber mixtures increased with the increase in FC, and reached a peak at FC = 1.0%. At FC = 1.0%, the $\gamma_{d\text{max}}$ increased about 11% higher than the soil without fiber additives as shown in Figure 3.14. Moreover, the value of OMC varied within approximately 13% lower than that of the soil without fiber additives. It is believed that the change behavior is mainly due to the displacement and rearrangement of soil particles induced by inclusion of fiber. With higher FC, more fibers filled the soil voids and therefore the soil specimen density became higher. In the case of FC = 1.2%, $\gamma_{d\text{max}}$ decreased while OMC increased as compared with the case of FC = 1.0%. This behavior implies that there is an optimum value of FC in this study. Moreover, it can be explained that this behavior might be due to the rearrangement of soil particles and fibers. Fibers may not effectively fill in the pore spaces of the soil-fiber mixture and could not fully contact with soil particles. As a result, $\gamma_{d\text{max}}$ decreased.

An attempt was made to correlate $\gamma_{d\text{max}}$ and OMC to verify whether such correlation exists between soil-fiber mixtures and other similar soils which were used in this study. The correlation was made using the author’s data (7 data points) and other data from published literature such as Wesley L.D. (1973) (20 data points), Gurtug and Sridharan (2004) (76 data points). Figure 3.15 shows the relationship between $\gamma_{d\text{max}}$ and OMC for various soils including natural and soil with fiber additives which were used in this study. It indicates that there is a good relationship between $\gamma_{d\text{max}}$ and OMC with a high correlation coefficient, $R^2 = 0.97$ and expressed by:

$$\gamma_{d\text{max}} = 21.28 \ e^{-0.0133 \ OMC} \quad (3.8)$$

where $\gamma_{d\text{max}}$ is the maximum dry unit weight and OMC is the optimum moisture content. Moreover, from Figure 3.15, it can be seen that the data obtained from this study are consistent with the previous studies, indicating that the compaction results presented in this study are uniquely related.
Figure 3.13  Standard proctor compaction curves for the Akaboku soil with various fiber contents

Figure 3.14  Change in $\gamma_{d,\text{max}}$ with various fiber contents
3.4.2 Unconfined Compressive Strength

The unconfined compression test shows that the fiber additives have a significant effect on the stress-strain behavior of the soil-fiber mixture. Figure 3.16 shows the relation between the compressive stress and axial strain ($\varepsilon$) of soil-fiber mixtures tested. The variation of $q_u$ and $\varepsilon_f$ with various fiber contents are showed in Figure 3.17. The addition of fibers increased the peak stress and ductility of the soil specimen. The values of $q_u$ and $\varepsilon_f$ of the soil specimens are given in Table 3.4. For any FC studied, the $q_u$ increased and reach a peak value at FC = 1.0%, and then decreased at FC = 1.2 %. The maximum value of $q_u$ (FC = 1.0%) increased about 80% as compared with FC = 0%. The mechanism that fiber inclusion increased the shear strength of soil-fiber mixture could be explained by the development of interfacial force and interlock between soil particles and fibers. The total contact area between soil particles and fibers increased with the increase in the FC, which contributed to the increase in the resistance to externally applied forces, and consequently the strength of the soil-fiber mixtures increases.
Table 3.4  Value of $q_u$ and $\varepsilon_f$ for various fiber contents

<table>
<thead>
<tr>
<th>Fiber content (%)</th>
<th>Compression test</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$q_u$ (kN/m$^2$)</td>
<td>$\varepsilon_f$ (%)</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>46.02</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>61.82</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>63.98</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>65.61</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>69.48</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>82.54</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>75.52</td>
<td>4.2</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.16  Stress-strain curves of Akaboku soil with various fiber contents

50
Furthermore, in the Figure 3.17, the soil-fiber mixtures exhibited a highly ductile behavior which is indicated by less loss of peak strength and larger $\varepsilon_f$ value. The similar trend with the $q_u$ is shown for the $\varepsilon_f$ at various FC. With increase in FC, the $\varepsilon_f$ increased up to FC = 1.0%, and slightly decreased with FC = 1.2%. This behavior can be attributed to the increased in the bonding resistance with the increase in FC. However, at FC = 1.2%, the effective interface contact between the soil particle and the fiber would be less. Therefore, the $q_u$ and $\varepsilon_f$ tend to decrease. The above observation indicates an improvement of the mechanical properties that the soil-fiber mixtures are able to hold more deformation and higher strain at rupture.

The elasticity modulus (E) is often used to characterize the stiffness of the soil. The relationship between the $E_{50}$ and FC were plotted in Figure 3.18. At the FC $\leq$ 0.6%, the lower stiffness value was found compared to the soil with FC = 0%. On the other hand, when the FC = 0.8% or above, the higher $q_u$ tends to be associated with higher secant modulus, and the stiffness became higher and the stress-strain curves changes became more ductile behavior. It can be concluded that in terms of the stiffness and ductile behavior with different FC, the effectiveness of the fiber additive was found for the FC $\geq$ 0.8%.

Figure 3.19 shows the normalized stress-strain curve of the soils at different FC. From the normalized stress-strain curves, the values of $TI$ were determined for soils at various FC. The $f'(\varepsilon')$ equations of each FC curve were tabulated in Table 3.5. Figure 3.20 shows the Toughness Index ($TI$) of the Akaboku soil with various FC. It can be seen that the $TI$ increased as the FC increases. Initially, a slightly increase of the $TI$ occurred up to FC = 0.8% and significantly increased for the FC $> 0.8%$. This result indicated that the soil-fiber mixtures can absorb much energy against induced strain, and subsequently the stress-strain curves change to a ductile behavior.
Figure 3.17  Variation of strength and strain with various fiber contents

Figure 3.18  Variation of modulus elasticity ($E_{50}$) for various fiber contents
Table 3.5 The equation of \( f(\varepsilon') \) for various fiber contents

<table>
<thead>
<tr>
<th>Fiber content (%)</th>
<th>( f(\varepsilon') )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>(-2.98 x^6 + 9.65 x^5 - 12.79 x^4 + 8.29 x^3 - 2.91 x^2 + 1.74 x + 0.0012)</td>
</tr>
<tr>
<td>0.2</td>
<td>(-1.15 x^3 + 1.22 x^2 + 0.89 x + 0.0056)</td>
</tr>
<tr>
<td>0.4</td>
<td>(-1.20 x^3 + 1.16 x^2 + 1.01 x + 0.0293)</td>
</tr>
<tr>
<td>0.6</td>
<td>(-1.37 x^3 + 1.60 x^2 + 0.78 x - 0.0227)</td>
</tr>
<tr>
<td>0.8</td>
<td>(-0.99 x^3 + 0.75 x^2 + 1.31 x - 0.0511)</td>
</tr>
<tr>
<td>1.0</td>
<td>(-0.03 x^3 - 0.95 x^2 + 1.98 x + 0.0027)</td>
</tr>
<tr>
<td>1.2</td>
<td>(0.26 x^3 - 1.52 x^2 + 2.25 x - 0.0005)</td>
</tr>
</tbody>
</table>

Figure 3.19 Normalized stress-strain curve
3.4.3 Tensile Strength

The tensile strength ($\sigma_T$) behavior at different FC indicated that the inclusion of fibers increased the $\sigma_T$ of the soil as shown in Figure 3.21. The results of the tensile test with various FC are summarized in Table 3.6. Initially $\sigma_T$ increased up to FC = 1.0% and decreased for FC = 1.2%. The results indicated that for the FC used, the value of $\sigma_T$ varied between 9.53 (FC = 0%) and 27.53 kN/m² (FC = 1.0%) and was found increased by 240% as compared to natural soil. This trend is similar to the unconfined compression test result in the previous section.

The effectiveness of fiber additives depends on the interaction between fibers and soil. The mechanism of the fibers interacts to the Akaboku soil mainly controlled by the adhesion force. When the tensile force needs to be mobilized in the fibers, such as that
which occurs in a desiccation cracks and differential settlement, only adhesion restrain the fibers from pullout and allows for its tensile resistance to develop. The amount of the adhesion force developed related to the surface contact area of the fibers in the soil (Ziegler et al., 1998). It can be explained that the adhesion force increased by increasing the surface contact area between the soil and fibers as can be achieved by increase the FC in the soil specimens. In the case of FC = 1.2%, the decreased in $\sigma_T$ might be due to the fibers not effectively fill in the pore spaces of the soil-fiber mixture and therefore the tensile resistance could not fully mobilized. Cai et al. (2006) conducted Scan Electrone Microscope (SEM) test to analyze the improving mechanism of fiber. It is clearly seen that after shearing, some fibers were left in soil with part of length exposed to the air and some threadlike grooves appear in the shear plane. This is probably due to the strong resistance of fiber to tension. Furthermore, in the Figure 3.21, the soil-fiber mixtures exhibited a highly ductile behavior which is indicated by larger $\varepsilon_f T$ value. The similar trend with the $\sigma_T$ is shown for the $\varepsilon_f T$ at various FC. With increase in FC, the $\varepsilon_f T$ increased up to FC = 1.0%, and decreased for FC = 1.2%. Sobhan and Mashnad (2002) reported that the fiber-reinforced specimens of the lightly stabilized soil had a higher tensile strength than the unreinforced specimens, and showed a gradual post peak decline in the load-carrying capacity which conform the results obtained in this study. Moreover, the fiber additives provide the linkage effect in the soil-fiber mixtures to suppress the development of tension cracks as shown in Figure 3.22.

<table>
<thead>
<tr>
<th>Fiber content (%)</th>
<th>Tensile test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_T$ (kN/m$^2$)</td>
</tr>
<tr>
<td>0.0</td>
<td>9.53</td>
</tr>
<tr>
<td>0.2</td>
<td>13.55</td>
</tr>
<tr>
<td>0.4</td>
<td>16.73</td>
</tr>
<tr>
<td>0.6</td>
<td>22.23</td>
</tr>
<tr>
<td>0.8</td>
<td>26.68</td>
</tr>
<tr>
<td>1.0</td>
<td>27.53</td>
</tr>
<tr>
<td>1.2</td>
<td>26.47</td>
</tr>
</tbody>
</table>
Figure 3.21  Variation of tensile strength and strain with various fiber contents

Figure 3.22  The linkage behavior of fiber admixtures in suppressing the cracks in tensile test
3.4.4 Shear Strength

The direct shear test was conducted to evaluate the strength properties of compacted Akaboku soil with and without fiber additives as a material for cover barrier layer in landfill cover system. The cohesion (c), internal friction angle (φ) of soil-fiber mixtures tested are shown in Figure 3.23. The values of cohesion and internal friction angle obtained from direct shear test are presented in Table 3.7.

Figure 3.24 shows the variation of cohesion and internal friction angle with various FC. It can be seen that an increasing in the FC, the cohesion increased significantly. The cohesion increased and range from 6.5 to 18 kN/m² which is almost 3 orders of magnitude. It is believed that the higher value of cohesion mainly due to fiber addition to the soil specimen. However, the internal friction was found slightly decreased with increasing in the FC of the soil specimens. The internal friction angle was found decreased and range from 18° to 15°. It is indicated that the shear strength of the compacted soil-fiber mixture mainly controlled by the cohesion rather than the angle of internal friction itself. However, Cai et al (2006) investigated that the addition of amounts of fiber and lime have the significant influence on the development of cohesion and internal friction angle. Tang et al (2007) also reported that similar behavior was observed for the cohesion and internal friction angle with addition of fiber and cement. The cohesion and internal friction angle of cemented soil increased with increasing in the FC.

<table>
<thead>
<tr>
<th>Fiber content (%)</th>
<th>Cohesion (kN/m²)</th>
<th>Internal friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>6.5</td>
<td>18</td>
</tr>
<tr>
<td>0.2</td>
<td>9.5</td>
<td>17</td>
</tr>
<tr>
<td>0.4</td>
<td>12.0</td>
<td>17</td>
</tr>
<tr>
<td>0.6</td>
<td>14.0</td>
<td>16</td>
</tr>
<tr>
<td>0.8</td>
<td>15.5</td>
<td>16</td>
</tr>
<tr>
<td>1.0</td>
<td>17.0</td>
<td>15</td>
</tr>
<tr>
<td>1.2</td>
<td>18.0</td>
<td>15</td>
</tr>
</tbody>
</table>
Figure 3.23 Shear strength of Akaboku soil with various fiber contents
The most important parameter for landfill cover barrier applications can be evaluated by using hydraulic conductivity. Table 3.8 shows the value of fiber content, molding water content, dry unit weight, and saturated hydraulic conductivity. With the increase in FC, the hydraulic conductivity of the soils firstly decreased and then increased as shown in Figure 3.25. The results show that the hydraulic conductivity changing from $5.8 \times 10^{-7}$ to $2.1 \times 10^{-6}$ cm/s. The lowest hydraulic conductivity was found for FC = 0.2% which is approximately $3.3 \times 10^{-7}$ cm/s. The increase in hydraulic conductivity was most significant for FC > 0.8%, which is conform to the previous study by Miller and Rifai (2004). According to USEPA (1989) regulation for non-hazardous waste facility, the barrier layer should have the hydraulic conductivity ($k$) $\leq 1 \times 10^{-5}$ cm/s. In this study, fiber contents up to 1.20% maintained the hydraulic conductivity ($2.1 \times 10^{-6}$ cm/s) within acceptable limit. The aforementioned test results indicate that this soil-fiber mixture can be potentially used as a material for landfill cover barrier layer.

### Figure 3.24
Variation in cohesion and internal friction angle with various fiber contents
An investigation of alternative material potentially used as a landfill cover barrier was conducted by several researchers. The study of using waste sludge (i.e. paper sludge and construction sludge) was conducted by Inazumi (2003) shows that the hydraulic conductivity of compacted construction sludge can satisfy the requirements by the USEPA. Another study was performed by Leung and Vipulanandan (1995) as an attempt to reduce the hydraulic conductivity of cracked samples of field clay and a clay-sand mixture. The results indicated that hydraulic conductivity was reduced from over $10^{-2}$ to far less than $10^{-7}$ cm/s. Miller and Rifai (2004) conducted a study of hydraulic conductivity by using polypropylene fibers. The results show that the hydraulic conductivity increased with increasing in the fiber content and also found the fiber contents up to 0.5% maintained the hydraulic conductivity within acceptable levels. However, in this study the fiber content up to 1.2% was found maintained the hydraulic conductivity within acceptable limit. Moreover, based on the hydraulic conductivity of soil-fiber mixtures used in this study, it is indicated that there is some potential for the use of fiber additives in engineering practice (i.e. landfill cover barrier system).

<table>
<thead>
<tr>
<th>Fiber content (%)</th>
<th>Max. dry unit weight (kN/m$^3$)</th>
<th>Molding water content (%)</th>
<th>Hydraulic conductivity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>8.13</td>
<td>78.0</td>
<td>$5.8 \times 10^{-7}$</td>
</tr>
<tr>
<td>0.2</td>
<td>8.19</td>
<td>74.0</td>
<td>$3.3 \times 10^{-7}$</td>
</tr>
<tr>
<td>0.4</td>
<td>8.27</td>
<td>73.0</td>
<td>$4.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>0.6</td>
<td>8.58</td>
<td>69.3</td>
<td>$4.6 \times 10^{-7}$</td>
</tr>
<tr>
<td>0.8</td>
<td>8.73</td>
<td>68.2</td>
<td>$6.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>1.0</td>
<td>9.03</td>
<td>65.0</td>
<td>$8.6 \times 10^{-7}$</td>
</tr>
<tr>
<td>1.2</td>
<td>8.42</td>
<td>70.8</td>
<td>$2.1 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
3.4.6 Interrelationship between Parameters

Studying the relationship between soil mechanical properties is useful in estimating the appropriate property that should be used in specific condition. In geotechnical engineering practice, it is useful to use simple physical properties such as dry density to predict the strength. In this study, the relationship between the soil parameters such as $\gamma_{\text{dmax}}$, $q_u$ and $\sigma_T$ for various of FC were investigated. From Figure 3.26(a), it can be seen that the $q_u$ increased with increasing in $\gamma_{\text{dmax}}$. The relationship between $\gamma_{\text{dmax}}$ and $q_u$ is obtained as:

$$q_u = 29.8 \gamma_{\text{dmax}} - 187.8 \quad (3.9)$$

The relationship between $\gamma_{\text{dmax}}$ and $\sigma_T$ is presented in Figure 3.26(b), and relationship is obtained as:

$$\sigma_T = 19.6 \gamma_{\text{dmax}} - 147.4 \quad (3.10)$$
Figure 3.26  Relation between $\gamma_{\text{dmax}}$ and $q_u$-$\sigma_T$ with various fiber contents
(a) $\gamma_{\text{dmax}}$ versus $q_u$,  (b) $\gamma_{\text{dmax}}$ versus $\sigma_T$

\[ q_u = 29.8 \gamma_{\text{dmax}} - 187.8 \quad \text{R}^2 = 0.792 \]

\[ \sigma_T = 19.6 \gamma_{\text{dmax}} - 147.4 \quad \text{R}^2 = 0.908 \]
In general, the $q_u$ and $\sigma_T$ generally increased with increasing $\gamma_{d\max}$. Moreover, the relationship between $q_u$ and $\sigma_T$ was also observed in this study, as shown in Figure 3.27. The relationship between $\sigma_T$ and $q_u$ is obtained as:

$$\sigma_T = 0.5665 q_u - 17.178$$

The interrelationships show a good correlation for all parameters investigated. The equation obtained from this interrelationship can be used interchangeably to predict the values of $\sigma_T$ and $q_u$.

### 3.5 Summary

In order to study the potential future uses of the landfill site for other applications (i.e. residential, park, sports fields, etc.), some of the geotechnical properties need to be investigated when the landfill cover is used as a bearing layer during the post-closure
period. The inclusion of fiber additive to the Akaboku soil as a material for the landfill cover barrier layer indicated an improvement of the geotechnical properties of soil specimens. The test results show the potential of using the soil-fiber mixture as a barrier material for landfill cover system. The experimental study in this chapter leads to the following conclusions:

1. The contribution of fiber to the compaction characteristics (i.e. maximum dry unit weight) increases with increasing fiber contents. A slight decrease of the maximum dry unit weight was found for fiber content of 1.2%, which indicate that there is an optimum value of fiber content.
2. The fiber inclusion increased the compressive strength, ductility, and decreased the loss of the post-peak strength. Furthermore, with the inclusion of fibers, the toughness index of the soil-fiber mixtures increases which indicates that the energy absorbing capacity increases, resulting in higher ductility in the post-peak region.
3. The inclusion of fibers increased the tensile strength of the soil-fiber mixtures. This is mainly due to the increase in the adhesion force as the surface contact area between the soil and fibers increase by increasing the fiber content.
4. The highest compressive and tensile strength of soil-fiber mixtures occurred at the highest dry density of the soil specimen due to the rearrangement and dense packing of the particles by inclusion of fibers. Furthermore, with the inclusion of fibers, the ductility tends to increased and decreased the loss of the post-peak strength.
5. The shear strength of the compacted soil-fiber mixture increased with the fiber inclusion and was found that the improvement of shear strength mainly controlled by the cohesion.
6. The hydraulic conductivity of soil-fiber mixtures increased with increasing fiber content. However, the hydraulic conductivity in the range of fiber contents used in this study is within the acceptable limit and can satisfy the requirement for hydraulic conductivity of landfill covers provided by USEPA.
7. Significant improvements in the mechanical behavior of the soil-fiber mixtures indicate that there is some potential for the use of fiber additives in engineering practice (i.e. landfill cover barrier material).
References


INVESTIGATION ON DESICCATION CRACK BEHAVIOR OF SOIL-FIBER MIXTURES

4.1 General

Compacted cohesive soils with low hydraulic conductivity are commonly used as a landfill cover barrier and bottom liner material. Development of cracks can be due to various processes including desiccation and shrinkage, freezing and thawing, differential settlement, and penetration by roots. Regarding the long term performance of the cover barrier system, the desiccation cracking of compacted clay liners is the central relevancy because desiccation will cause cracks in the compacted soil liner and consequently reduce the sealing effect of the cover system dramatically (Witt and Zeh, 2005).

Desiccation of clay liners is a major factor affecting landfill performance. Desiccation leads to the development of shrinkage cracks. Cracks provide pathway for moisture migration into the landfill cell which increases the generation of waste leachate, and ultimately increase the potential for soil and groundwater contamination (Miller et al. 1998). Moreover, Desiccation cracks can also form macrospores. This phenomenon is important in environmental applications due to its impact on groundwater and vadoze zone transport rates.

A variety of research efforts have been attempted to overcome the problems of desiccation cracking in landfill cover system. Some have considered the use of surface moisture
barriers above the soil layer (Albright et al., 2004). A few have considered soil additives (lime, sand, and cement) to increase the soil strength and resistance to cracking (Leung and Vipulanandan, 1995; Omidi et al., 1996). Based on the previous study, the lime or cement additives would not sufficiently suppress the desiccation crack of clayey soils with high water contents. However, using fiber as additives to suppress the desiccation problem commonly encountered in the landfill cover barrier material has not received sufficient attention.

In this chapter, the study was conducted to investigate the influence of $\text{C}_3\text{H}_6$ (polypropylene) fiber additives on the compacted Akaboku soil potentially used as a material for landfill cover barrier system. The laboratory tests were conducted to investigate the effects of fiber additives on the desiccation crack and volumetric shrinkage behaviour of compacted Akaboku soils.

4.2 Soil Desiccation

4.2.1 Desiccation Cracking on Compacted Soil

Compacted soil liners have been used for many years as engineered hydraulic barriers for waste containment facilities. Some bottom liners and cover systems contain a single compacted soil liner, but others may contain two or more compacted soil liner. Another key issue is that the cover system is always exposed to a changing weather condition because it is generally close proximity to the atmospheric environment. The barrier material (compacted soil) generally shows shrinkage behavior under drying condition. Moreover, cracks developed due to the excessive shrinkage during the desiccation process.

Desiccation cracking of compacted soil is a problem encountered in many engineering disciplines, including geotechnical and geoenvironmental engineering. The problems associated with desiccation cracks in soil include expansion of the soils upon wetting and softening the soils as a result of water entering the soil structure (Mitchell 1993). Bosscher and Connell (1988) showed that jointing in desiccated clay has significant effects on the hydraulic conductivity, shear strength, compressibility, and slope stability of the soils used. Albrecht and Benson (2001) showed that due to desiccation cracking the hydraulic
conductivity increased about three orders of magnitude. Omidi et al. (1996) investigated the relationship between the volumetric shrinkage and hydraulic conductivity of compacted soils. They concluded that only soil with a volumetric shrinkage strain less than 11% should be used for the construction of liners to avoid the significant increase in the hydraulic conductivity.

Observation of cracking of compacted liner soils in the field have been presented in various studies. Basnett and Brungard (1992) observed desiccation cracks on the side slopes of a clay liner during landfill construction. The cracks were 13-25 mm in width and extended to a depth of 0.3 m. Miller and Mishra (1989) observed desiccation crack during their field investigation of landfill liners. The cracks exceeded 10 mm in width and some penetrated the entire depth (0.3 m) of the compacted clay layer. Montgomery and Parsons (1989) observed desiccation cracking for 3 years, the upper 0.2-0.25 m of the compacted clay had become desiccated, with crack widths exceeding 13 mm. The results indicated that some cracks can penetrate to the entire thickness of the compacted soil.

4.2.2 Utilization of Fiber in Compacted Soil

In recent years, the interest of using fibers has arisen to suppress desiccation cracks problem. Polypropylene fiber is becoming a common synthetic material used to reinforce soil and concrete (Maher and Ho 1994; Nataraj and McManis 1997; Synthetic Industries 1998). The primary attraction is due to its low cost (Moncrieff 1979). Polypropylene fiber is easy to mix with soil and has relatively high melting point which makes it possible to determine the water content of soil-fiber mixture without changing the physical properties. Also, polypropylene fiber is a hydrophobic and chemically inert material which does not absorb or react with the soil moisture or leachate. Miller and Rifai (2004) conducted a study using fiber as reinforcement for the soil liners. The study showed that with the increase in the fiber contents, the crack reduction and the hydraulic conductivity increased. However, the change in the other engineering properties, such as shrinkage limit, dry density, and volumetric shrinkage strain during desiccation crack were not investigated. The polypropylene fiber additives could reduce the amount of shrink/swell and tension cracks in compacted clays (Al Wahab and El-Kedrah, 1995). The compacted rubber fiber-clay was used to increase the shear strength of the composite soil (Ozkul and Baykal,
2007). The previous studies (Park and Tan, 2005) showed that the inclusion of short fiber increases the strength and subsequently improves the stability of the soil. Tang et al. (2007) concluded that the fiber as additives would cause an increase in the strength and ductility, while decrease in the stiffness of the cement stabilized clays. However, using fiber as additives to suppress the desiccation problem commonly encountered in the landfill cover hydraulic barrier material has not received sufficient attention.

4.3 Materials and Testing Equipment

4.3.1 Material Used

The materials used in this study are Akaboku soil and polypropylene (C₃H₆) fiber. The Akaboku soil was sampled from Kumamoto Prefecture, Kyushu Island, Japan. The soil specimen was collected on the site by using excavator at 2 m depth from the surface ground. The soils were kept in a box under room conditions (25±2°C, 50±1% relative humidity) prior to testing. Furthermore, the fiber used in this study as an additive material is polypropylene fiber (RCP17T) with 10mm length and 50 µm in diameter. The properties of the material used in this study are presented in the previous chapter.

4.3.2 Testing Equipment

The standard Proctor compaction apparatus was used to compact the soil samples at various water contents according to ASTM D698-70. Compaction energy was equal to the compaction energy used in standard Proctor compaction tests, 593 kJm⁻³. The testing equipment consisted of soil mold (cylinder) with 10 cm in height, 30 and 80 cm in diameter, a drying system (fan), camera (Canon EOS, zoom lens EF 55-200 mm 1:4.5 – 5.6), vernier caliper for measuring the deformation of soil, balance, and thin wire for measuring the crack depth. The desiccation test equipment was design with the purpose to simulate the desiccation cracks behavior of the compacted Akaboku soil with and without fiber additive during desiccation process.
4.4 Testing Procedures

4.4.1 Experimental Setup

The desiccation crack test, soil specimens were prepared with 30 cm in diameter and 10 cm in height. The experimental setup consisted of soil mold, a drying system (fan), camera as shown in Figure 4.1. Soils used in this study were compacted in the mold under the conditions of maximum dry unit weight and optimum moisture content (OMC). According to Haines (1923), specimens compacted at OMC have the largest volume of soil particles and the least volume of water/unit volume of soil at any given compactive effort. A fan was used to simulate wind condition on the soil surface and to increase the rate of air drying under room conditions (20 ± 2°C, 35 – 60% relative humidity). A camera was mounted 50 cm above the mold to record image periodically of the soil surface undergoing drying process. The specimens were prepared by mixing the soil with various percentages of fiber content (FC) and the percentages of mixtures (by weight) presented in Table 4.1.

Table 4.1 Composition of mixtures

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>By weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natural soil (0.0 % Fiber)</td>
</tr>
<tr>
<td>2</td>
<td>0.2 % Fiber</td>
</tr>
<tr>
<td>3</td>
<td>0.4 % Fiber</td>
</tr>
<tr>
<td>4</td>
<td>0.6 % Fiber</td>
</tr>
<tr>
<td>5</td>
<td>0.8 % Fiber</td>
</tr>
<tr>
<td>6</td>
<td>1.0 % Fiber</td>
</tr>
<tr>
<td>7</td>
<td>1.2 % Fiber</td>
</tr>
</tbody>
</table>

4.4.2 Desiccation Stage

The drying process was conducted for a period of approximately 30 days. The weight, height, diameter, and deformation of each specimen were measured periodically. The
volume change was used to determine the volumetric shrinkage strain of the soil specimens. The volumetric shrinkage strain is defined as the change in volume ($\Delta V$) to the total volume of the soil specimens ($V$) (%), expressed by:

$$\text{Volumetric shrinkage strain} = \frac{\Delta V}{V} \times 100\% \quad (4.1)$$

The surficial dimensions of cracks were monitored during the tests. Crack dimension are generally measured using approximate methods. In this study, crack dimension are measured using an image pixel method. DataPicker ver.1.2 was used to analyze the digital photographs of desiccating soils to obtain the crack area. The photograph of the soil specimens were taken every 24 hours. Kleppe and Olson (1985) developed a scale that ranged from 0 to 4 to describe severity of cracking. A crack severity number of 0 indicates absence of cracking, whereas, cracks with widths $> 20$ mm and with substantial depths are described by crack severity number 4. Al Wahab and El-Kedrah (1995) developed a cracking index to quantify the extent of cracking. The cracking index is the ratio of the area of cracks to the total surface area of soil. The area of crack is equal to the product of its length and width. Calculations were made for crack depths exceeding 2 mm. Al Wahab and El-Kedrah (1995) did not present methods for the determination of the length and width of cracks. It is believed that these dimensions were determined using a ruler. This potentially leads to overlooking the effects of the irregular shape of cracks in the calculation of the cracking index. Mi (1995) and Miller et al (1998) describe a similar approach in order to determine the Crack Intensity Factor (CIF). The CIF was used as a parameter to evaluate the quantity of desiccation cracks developed in the soils. The CIF was introduced as a descriptor of the extent of surficial cracking and expressed by:

$$\text{CIF} = \frac{A_C}{A_t} \quad (4.2)$$

in which $A_C$ is the desiccation crack area, and $A_t$ is the total surface area of soils. In this study, only the cracks with width greater than 0.5 mm were accounted for the determination of the crack area and CIF index. The maximum crack depth was measured using thin gauge wires.
Figure 4.1    Desiccation crack test setup

Figure 4.2    The surficial cracks were monitored by photographs using digital camera ($\phi = 30$ cm)
4.5 Test Results and Discussion

4.5.1 Variation in Mass and Water Content with Time

The normalized mass was presented in Figure 4.3(a). The mass was normalized by dividing the weight of soil specimen at each time $W(t)$ by the initial weight of soil specimen $W(0)$. The results showed that for the lower FC (i.e. FC = 0.2 and 0.4%) at the same elapsed time (i.e. at 5 days), the rate of mass change is greater than that for higher FC. The change in mass progressed slowly after 20 days of the drying period. The lowest reduction in mass was found about 15% for FC = 1.0. For the soil without fiber additive, the reduction in mass at the end of the observation was found about 23% of the initial value. Albrecht and Benson (2001) conducted desiccation test for a period of approximately 10 days and the results showed that no significant mass or volume changes occurred past the first week of drying stage. Furthermore, similar behavior also found in the relationship between normalized water content and time as shown in Figure 4.3(b).

The water content was normalized by dividing the water content of soil specimen at each time $w(t)$ by the initial water content of soil specimen $w(0)$. It is observed that significant water content changes occurred at the first 10 days of the drying period. The rate of water content change became lower approximately after 20 days. Thus, subsequent change in water content of soils reached a steady-stable condition up to approximately 30 days. Moreover, the reduction about 48% was found for soil specimen with FC = 1.0% which indicated the lowest change in water content at the end of the desiccation crack test. This observation is consistent with the change in volume of the soils as presented in the later part. The behavior of soil-fiber mixtures on the volumetric shrinkage will be discussed in the following section. Haines (1923) described the drying process of saturated soils as having had two significant stages, referred as primary and residual drying. Figure 4.4 shows the stages during drying process. Primary drying is the first stage of drying, and occurs as water leaves the soil without entry of air. Since air is not entering the soil, the volume change is equal to the volume of water leaving the soil. The majority of the total volume change occurs during the primary stage of drying. Water surrounding the individual soil particles is removed, allowing the soil particles to move closer together as the water retreats. At some point the soil particles contact each other, and the drying
process slows as the structure of the soil begins to resist additional volume change. In this phase of drying, termed residual drying, air enters the soil and replaces the water being removed. Little change in soil structure or total volume occurs during residual drying because the particles in contact. Therefore, the total amount of volume change is closely related to relative volumes of water and solids present in the soil as drying begins.

Figure 4.3 Behavior of the Akaboku soil at various fiber contents during desiccation
(a) Change in normalized mass
(b) Change in normalized water content
Initially, variation in shrinkage limit with various fiber contents were analyzed as shown in Figure 4.5. The shrinkage limit increased with increasing in the FC and decreased at FC = 1.2%. It was found that the shrinkage limit significantly increased by about 20% at FC = 1.0% (peak value) as compared with FC = 0 %, and slightly decreased at FC = 1.2%. This may be mainly due to that at FC = 1.2%, more fibers filled the soil voids and adhered to each other to form lumps, which suppressed the contact between soil particles and fibers, and induced less resistance between soil particles and fibers. The elevated shrinkage limit of the soil with fiber additives would suppress the volumetric shrinkage, since the water content of the soils may easily reach the shrinkage limit during desiccation process. Therefore, soils have higher shrinkage limit may shrink less. This observation implies the fiber additives would minimize the volumetric shrinkage of landfill cover barrier when

4.5.2 Volumetric Shrinkage Strain

Initially, variation in shrinkage limit with various fiber contents were analyzed as shown in Figure 4.5. The shrinkage limit increased with increasing in the FC and decreased at FC = 1.2%. It was found that the shrinkage limit significantly increased by about 20% at FC = 1.0% (peak value) as compared with FC = 0 %, and slightly decreased at FC = 1.2%. This may be mainly due to that at FC = 1.2%, more fibers filled the soil voids and adhered to each other to form lumps, which suppressed the contact between soil particles and fibers, and induced less resistance between soil particles and fibers. The elevated shrinkage limit of the soil with fiber additives would suppress the volumetric shrinkage, since the water content of the soils may easily reach the shrinkage limit during desiccation process. Therefore, soils have higher shrinkage limit may shrink less. This observation implies the fiber additives would minimize the volumetric shrinkage of landfill cover barrier when
desiccation exists. The cover barrier with less shrinkage and contains fewer and smaller cracks should have higher effectiveness in mitigating the rainfall infiltration as compared with that contains larger cracks.

The change in dry unit weight ($\gamma_d$) of the soil was presented in Figure 4.6. The $\gamma_d$ increased with decreasing in water content. Since the water content decreased, the soil particles and fibers adhered to each other. The rearrangement of soil particles due to decreasing in water content induced more contact between fibers and soil particles and cause the soil specimen density became higher. The same mechanism also occurred for the soil without fiber additive. The highest value was found for the soil at FC = 1.0%. Moreover, the relationship between the normalized $\gamma_d$ and the normalized water content is presented in Figure 4.7. The $\gamma_d$ of soil specimens were normalized by dividing the value of $\gamma_d$ at each time ($\gamma_d(t)$) by the initial value of $\gamma_d$ ($\gamma_d(0)$). The normalized water content was defined by the water content of each time ($w(t)$) divided by initial water content ($w(0)$). The result shows that there is no significant change in the value of normalized $\gamma_d$ for all soils. The maximum difference of the normalized $\gamma_d$ is only 4%. The result implies that the effect of density on the shrinkage behavior of soil-fiber mixture could be slight.
Figure 4.6  Dry unit weight change with average water content at various fiber contents

Figure 4.7  Normalized dry unit weight change and water content for the Akaboku soil at various fiber contents
Albrecht and Benson (2001) conducted desiccation test on compacted natural clays to observe the volumetric shrinkage strain behavior. The volumetric shrinkage strain was found as a direct function of the volume of water/volume of soil when the soil is saturated. Factors that affect the amount of water contained in the soil include soil properties and compaction conditions. Soils with higher clay content and higher plasticity index generally have a greater volume of water and thus more prone to a large volumetric shrinkage strain during drying.

In this study, the volumetric shrinkage strains behavior of soil-fiber mixture were observed. Figure 4.8 shows the variation of volumetric shrinkage strain with fiber inclusion. It was found that with increasing in FC, the volumetric shrinkage strain of soil-fiber mixtures decreased. This behavior can be explained by that the total contact area between soil particles and fibers increased with increasing FC, which might have provided more resistance induced from the soil-fiber interaction during the desiccation (Cai et al. 2006). The optimum fiber content to achieve maximum volume change reduction was found to be 1.0%. However, exceeding a fiber content of 1.0% was not practical. In the case of FC = 1.2% did not significantly reduced the volumetric shrinkage strain. The main reason may be due to non homogenous distribution of fibers within the soil at FC = 1.2%. At FC = 1.2%, the fibers adhere to each other to form lumps and could not contact with soil particles fully and reduced the resistance between fibers and soil particles. It would be likely that too much fiber added could reduce the effectiveness of the improvement soil due to the fibers cannot fully contact with soil particles and subsequently reduce the resistance between fibers and soil particles. Furthermore, the lowest volumetric shrinkage strain reduction was found in the case of FC = 1.0%. The similar trends with the normalized water content were shown in Figure 4.9. It can be seen that there is no significant effect of the initial condition of water content on the volumetric shrinkage strain. As a result, the influencing factor would be only due to the fiber additives and the fiber content. Furthermore, the lowest value of volumetric shrinkage strain was observed at FC = 1.0%. The volumetric shrinkage strain decreased and range from 15.5% (FC = 0%) to 7.6% (FC = 1.0%) in the first ten days which represents approximately 51% reduction of volumetric shrinkage strain as compared to the soil without fiber additive as shown in Figure 4.10.
Figure 4.8  Volumetric shrinkage strain change with average water content at various fiber contents

Figure 4.9  Volumetric shrinkage strain change with normalized water content at various fiber contents
Variations in CIF with Various Fiber Contents

The CIF for all soils are presented in Figure 4.11. Cracks developed rapidly in the soil without fiber additive (FC = 0%) at the water content less than 50%. The maximum value of CIF was about 2.75% and essentially remained constant during the subsequent desiccation process. The CIF of the soil without fiber additive is much greater than the soil with fiber additives. The cracking behavior significantly affected by the change in the water content for natural soil (FC = 0%). It was observed that the extent of cracking is a function of the amount of water in the soil during drying process. Subsequent drying induced suction in the soil. When the suction exceeded the resistance of soil, cracks developed. Moreover, with inclusion of fiber, the friction between soil particles and fibers occurred and contributing to the generation of the resistance during the desiccation process. The soil-fiber resistance was mobilized when the soil tended to shrink. As a result, the cracks were effectively suppressed. Furthermore, the observed CIF for soils with fiber...
additives is almost zero except for FC = 1.0%, which corresponds to CIF of about 0.5% as shown in Figure 4.11. A small amount of cracks were found in soil at FC = 1.0%. It is believed that since the soil-fiber mixture at FC = 1.0% had the highest water content (Figure 4.3b) during drying period (after 2 weeks), the presence of relatively higher amount of water reduced the contribution of fibers to the composite resistance (interfacial force, interlock force, and friction) between the soil particles and fibers. Consequently, the cracks slightly developed in the soil-fiber mixtures at FC = 1.0%. Maher and Ho (1994) referred this phenomenon as the lubricating effect of water, which cause less load transfer between soil particles and fibers during loading.

![Figure 4.11 Crack intensity factor (CIF) for the Akaboku soil at various fiber contents](image)

Figure 4.11 Crack intensity factor (CIF) for the Akaboku soil at various fiber contents
Figure 4.12 shows the schematic diagram of the mechanical behavior at the interface between soil particles and fiber. It can be seen that the fiber surface is attached by many soil particles which make contribution to the strength and friction between soil particles and fiber. When the specimens are under load, the “linkage” effect of fiber can effectively impede the further development of tension cracks and the deformation of the soil.

Example of photographs of drying soil during the test is presented in Figure 4.13. The entire surface area of the soil specimen is shown in the photographs. Figure 4.13(a) and (b) indicate the picture of surficial cracking for natural (FC = 0%) and soil-fiber mixture (FC = 0.8%). The cracks were found in the soil at FC = 0% than those shown in the soil at FC = 0.8%. The most severe cracking occurred in specimen with the highest volumetric shrinkage strain (FC = 0%). In contrast, specimens with fiber additives had very small amount of cracks and these specimens had lower volumetric shrinkage strain.
Figure 4.13   Photograph of crack developed at the desiccation crack test
(a) FC = 0%
(b) FC = 0.8%
4.5.4 Crack Depth Prediction of the Compacted Soil-Fiber Mixtures

The relationship between water content ($w$) and the maximum crack depth ($D_{\text{max}}$) for the soil at $\text{FC} = 0\%$ (i.e. natural soil) is shown in Figure 4.14. Good correlation exists between $w$ and $D_{\text{max}}$ for soil at $\text{FC} = 0\%$, expressed by:

$$\ln D_{\text{max}} = 5.05 - 0.06w$$  \hspace{1cm} (4.3)

Other researcher (Yesiller et al. 2000) reported that the vertical cracks can be penetrated to the entire thickness (170mm) of the compacted soil specimen. In this study, the $D_{\text{max}}$ was found about 50\% (50mm) of total thickness of the soil specimen. Moreover, the equation 4 can be used as a simple method to predict the $D_{\text{max}}$ in practical application.

Figure 4.14  Relationship between maximum crack depth and water content
4.5.5 Improvement Method of Desiccation Crack Test

Although the soil-fiber mixture can effectively suppress the desiccation cracking in this study, the excessive volumetric shrinkage strain was found with the previous method (ϕ = 30 cm mold) due to a large lateral deformation. According to USEPA (1989), the volumetric shrinkage strain should be equal or less than 4%. Since there is a limitation was found in the 30 cm soil specimen such as a large lateral deformation, a bigger size mold was used to improve the method in the desiccation crack test. The mold with 80 cm in diameter and 6 cm in height was developed in the improvement desiccation crack test to simulate the real condition in the field. A sand layer was placed at the plate of mold to provide interface shear stress at the bottom of the soil specimen. Moreover, the adhesive material (concrete adhesive) was placed in the inner side of the mold to provide bonding effect between the soil specimen and mold and suppress the excessive lateral movement. Figure 4.15 shows the modified desiccation crack test setup. The photograph of sample used in the improvement desiccation crack test is shown in Figure 4.16. The method in measuring the volume change and deformation are similar with the smaller sample (30 cm). In order to measure the change in water content due to the difficulty to obtain the precise water content of 80 cm sample, the reference sample with 30 cm diameter were used to determine the water content in this improvement method.

Figure 4.17 shows the variation of volumetric shrinkage strain of the natural soil specimen (FC = 0%) with two different diameter (ϕ = 30 and 80 cm). In general, similar trend of volumetric shrinkage strain was found for both methods. The improvement method (ϕ = 80cm) showed the lower value of volumetric shrinkage strain than the previous method (ϕ = 30cm). The volumetric shrinkage strain of 80 cm sample reduced approximately 12% at the end of drying stage as compared to the 30 cm sample. It is believed that the sand layer at the bottom of soil specimen provide a friction between soil specimen and sand. Moreover, the bond between soil specimen and adhesive material in surrounding mold can reduce lateral movement of the soil specimen. As a result, a lower volumetric shrinkage strain was observed for the improvement method. Although, only natural soil was observed in this study, this result indicated that the potential of using this improvement method for soil-fiber mixture for future research.
Figure 4.15   Modified desiccation crack test setup

Figure 4.16   Photograph of the improvement sample (φ = 80 cm)
Summary

This chapter has described a study on desiccation cracking of Akaboku soil with fiber additive. From the results presented in this study, following conclusions can be drawn:

1. The improved soil-fiber mixtures enhance the beneficial changes in the engineering properties of the Akaboku soil (i.e. compaction characteristics, volumetric shrinkage strain, and the crack intensity factor). During the desiccation process, the volumetric shrinkage developed in the compacted Akaboku soil with and without fiber additives and substantially controlled by water content.

2. The shrinkage limit increased significantly with the inclusion of fibers. The elevated shrinkage limit of the soil with fiber additives would suppress the volumetric shrinkage, since the higher water content of the soil-fiber mixtures may easily reach its shrinkage limit during desiccation process.

Figure 4.17 Variation of volumetric shrinkage strain with two different diameter
3. With an increasing in the fiber content, the volumetric shrinkage strain decreased. The behavior of soil with and without fiber additives in the desiccation crack test would be only due to the fiber inclusions. Fiber inclusion increased the volumetric shrinkage strain reduction significantly. The volumetric shrinkage strain decreased approximately 51% within the range of fiber contents used in this study.

4. With the fiber additives, crack was significantly suppressed. The CIF decreased with increasing in the fiber content. This is mainly due to the interaction of soil particles and fibers, which enhanced the resistance against crack.

5. The deficiency of the 30 cm sample was observed in this study. The improvement method was introduced using a bigger soil sample (\(\phi = 80\text{cm}\)). The result showed that the improvement method has lower volumetric shrinkage strain value compare to pervious method (\(\phi = 30\text{cm}\)). This indicate that the potential of using this improvement method for future research.

6. This desiccation crack test suggests the potential application of the fiber additives to soils as an available method to suppress desiccation cracks encountered in landfill cover barriers.
References


5.1 General

Modern engineered landfills are designed to minimize or eliminate the constituents release to the environment. Solid and hazardous waste landfills are required by government or local regulations to cover waste materials prior to or as part of final closure. Moreover, successful design and construction of soil liners and covers involves many aspects such as selection of material, determination of construction methodology, analysis of slope stability and bearing capacity, evaluation of subsidence (settlement), and consideration of environmental factors (Daniel 1987; Daniel and Benson 1990).

Compacted soil is widely used as a material for landfill and waste impoundments. Most regulatory agencies required that the compacted soil liner and cover should be designed to meet the minimum design requirement. However, Daniel and Benson (1990) reported that rational design of the compacted soil liners should be based on the test data developed for each particular soil used. Furthermore, the compacted soil liner and cover system may also suffer damage from the desiccation cracking and differential settlement problems, consequently increase the hydraulic conductivity and reduce the sealing effect of the cover system dramatically (Albrecht and Benson, 2001; Witt and Zeh, 2005; Harianto et al., 2007).
Recently alternative material for cover lining system are designed and used in landfill due to the weakness of the conventional landfill material. The fiber was alternatively used as an additive material to overcome the desiccation problem and also found could increase the engineering properties of soil-fiber mixture (Miller and Rifai, 2004; Tang et al., 2007). Although soil-fiber mixture has been used successfully in many structure (i.e dams, embankment, etc.), the current information related to soil-fiber mixture use as a material for landfill cover barrier system is very limited. Moreover, consistent design and performance criteria specifically applicable to this method are not well established.

In this chapter, the criteria in order to design a landfill cover barrier layer using soil-fiber mixture material is proposed and provide the minimum design requirement for landfill cover barrier system. Moreover, suggestions are made for overall acceptable zone based on the five design parameters considered within which compacted test specimens will have low hydraulic conductivity ($\leq 1.0 \times 10^{-5}$ cm/sec), have a suitable mechanical properties for structural integrity, and resistant to cracks due to desiccation.

### 5.2 Compacted Soil Layer with Fiber (CRLF) in Landfill

#### 5.2.1 Covers and Liners Reinforced with Randomly Distributed Fibers

A promising alternative for stabilization of landfill liners and covers involve the use of fiber-reinforcement. The advantages of fiber-reinforcement over planar reinforcement in the stabilization of landfill are:

- Fiber reinforcement is particularly suitable for stabilization of veneer slopes, as it provides additional shear strength under low confining pressures. A small increase of shear strength under low confinement has a significant impact on the stability of shallow slopes.
- Randomly distributed fibers help maintaining strength isotropy and do not induce potential planes of weakness that can develop when using planar reinforcement elements.
- No anchorage is needed into solid waste as in the case of reinforcement with horizontal geosynthetics or at the crest of the slope as in the case of reinforcement parallel to the landfill slope.
- The fiber reinforcement has the potential of mitigating the potential for crack development, providing erosion control, and facilitating the establishment of vegetation.

Consequently, fiber reinforced liner and covers systems are expected to lead to economically and technically superior alternatives for reinforcement of final landfill liner and cover systems.

### 5.2.2 Soil-Fiber Mixture as a Material for Cover Barrier Layer

Innovative approaches have been recently implemented to reinforce landfill covers and base liners. Many efforts had been conducted by researchers to find the alternative materials for landfill covers and base liners. This includes the using of geosynthetic reinforcement and additive materials (lime, cement, and sand). Miller and Rifai (2004) conducted study on fiber reinforcement in the bottom liner system. The inclusion of fibers as a reinforcing material affected the soil compaction behavior and its hydraulic conductivity while the significant impact was on the cracking phenomena of the soil. This study presents a framework for the design of innovative final landfill cover barrier layer by using a soil-fiber mixture material. The compacted soil layer with fiber (CSLF) is proposed as a material for landfill cover barrier system. Furthermore, the fibers addition was found to enhance the strength of the soil specimen (Harianto et al. 2008). The application of soil-fiber mixtures as a material in landfill cover barrier layer would give a benefit in the future purpose such as the potential of using post-closure landfill as a park, sports venue, and residential area. Moreover, the most problem commonly encountered in landfill cover system is desiccation cracking in the drying period. Harianto et al. (2007) reported that the soil-fiber mixture can effectively suppress the desiccation crack problem. Furthermore, the volumetric shrinkage strain decreased approximately 51% as compared to the soil without fiber additive. The improved material (soil-fiber mixture) enhances the function of soil cover layer as a hydraulic barrier for waste containment systems by decreasing the crack potential. This indicated that the potential application of the soil-fiber mixture as an available method to suppress desiccation cracks encountered in landfill cover barriers and in engineering practice for future applications of post-closure landfill.
5.3 Design Criteria of Compacted Soil Layer with Fiber

The values of parameter used in chapter were obtained from the previous chapter (see Chapter 3 and 4). In this chapter, the parameters for the design of soil-fiber mixtures as a material for covers include compaction characteristics, unconfined compressive strength, cohesion, and tensile strength. The required value of each design parameters should meet with a minimum of 50% increasing in the value of each design parameter investigated compare to the natural soil. Moreover, for the hydraulic conductivity, the value should be less or equal to $1 \times 10^{-5}$ cm/s (non-hazardous waste). The value of crack intensity factor (CIF) should be 0%. The acceptable zone (AZ) should be drawn to encompass the data points representing test results meeting or exceeding the design criterion. The approach was constructed by drawing hatched position on the figure plane that the FC meets the design criterion. Using the method of superimposition, overall AZ was constructed to the soil specimens.

The optimum FC that meets all the design criteria is defined as the FC that is necessary to achieve the maximum dry unit weight, maximum shear and tensile strength, maximum cohesion, minimum hydraulic conductivity, and minimum amount of cracking. The value should maximize the benefits of fiber inclusion in terms of all parameters mentioned previously.

5.3.1 Compaction Characteristics

The common and modern compaction control criteria widely used for construction quality assurance as part of the design process for compacted soil liners and covers. Osinubi and Nwaivwu (2006) reported that compaction control criteria can be used in the design of compacted lateritic soil liner and covers. Overall acceptable zones were constructed on the compaction plane to meet design objectives for all design parameters.

The relationship of maximum dry unit weight ($\gamma_{d\ max}$) and FC are shown in Figure 5.1. The $\gamma_{d\ max}$ generally increased with increasing in the FC. However, the $\gamma_{d\ max}$ first increased up to FC = 1.0%, and then decreased at higher value of FC (FC = 1.2%). The maximum value
of the $\gamma_{d_{\text{max}}}$ was obtained in the FC= 1.0%, which about 11.1% higher than that of the soil without fiber additives. However, values of the $\gamma_{d_{\text{max}}}$ for each FC investigated fall within very narrow ranges and the variations in the $\gamma_{d_{\text{max}}}$ are found less than 50%, which is considered insignificant.

5.3.2 Adequate Compressive and Tensile Strength

Figure 5.2 shows the variation of unconfined compressive strength ($q_u$) with various FC. Significant improvement in compressive strength (more than 50%) was found for fiber contents between 0.8 and 1.2%. The $q_u$ first increased and later decreased at higher of FC (i.e. FC = 1.2%). The trend here suggests that variation in $q_u$ depend on the FC. The maximum value of $q_u$ was found at FC = 1.0% and indicated increase about 79.4% as compared with FC = 0%. Moreover, it can be seen that for FC = 0.8 to 1.2% were found to meet the design criterion. The AZ as shown in Figure 5.2 indicates portion on the figure plane in which the $q_u$ values increased equal or more than 50% compare to the natural soil.

Similar relationship was also obtained for tensile strength with various FC as shown in Figure 5.3. The value of tensile strength generally increased up to FC = 1.0% and then
decreased of FC = 1.2%. The fiber content between 0.4 and 1.2% were found to meet the design condition. The AZ was determined based on the procedures in the previous section.

Figure 5.2  Acceptable zone based on unconfined compressive strength consideration

Figure 5.3   Acceptable zone based on tensile strength consideration
5.3.3 Adequate Cohesion and Internal Friction Angle

Figure 5.4 shows the variation of cohesion and internal friction angle with various FC. It can be seen that an increasing in the FC, the cohesion increased significantly. The improvement in cohesion based on the criterion defined previously (more than 50%) was found for FC between 0.4 and 1.2%. The cohesion increased and range from 6.5 to 18 kN/m² which is almost 3 orders of magnitude. However, the internal friction was found slightly decreased with increasing in the FC of the soil specimens. The internal friction angle was found decreased and range from 18° to 15° (see Chapter 3). Therefore, the internal friction angle was not taken into consideration for design criteria in this study. Moreover, it is indicated that the shear strength of the compacted soil-fiber mixture mainly controlled by the cohesion rather than the angle of internal friction itself.

![Figure 5.4 Acceptable zone based on cohesion consideration](image)

Figure 5.4 Acceptable zone based on cohesion consideration
5.3.4 Low Hydraulic Conductivity

Hydraulic conductivity is the key parameter for most compacted clay liners and covers. A great attention generally focused on achieving low hydraulic conductivity (Qian et al. 2002). In this study, the soil-fiber mixtures were used to investigate the change of hydraulic conductivity in order to determine the acceptable value of FC with low hydraulic conductivity. Figure 5.5 shows the relationship between hydraulic conductivity and FC. The hydraulic conductivity is plotted as a function of fiber content. The slight decreased of hydraulic conductivity found for FC = 0.2 to 0.6% and increased for higher FC. The increase in hydraulic conductivity was most significant for FC exceeding 0.8% which consistent with the previous study by Miller and Rifai (2004). According to USEPA (1989) regulation for non-hazardous waste facility, the barrier layer should have the hydraulic conductivity \( k \leq 1 \times 10^{-5} \) cm/s. In this study, fiber contents up to 1.2% maintained the hydraulic conductivity within acceptable limit.

![Figure 5.5 Change in hydraulic conductivity with various fiber contents](image-url)
5.3.5 Minimum Crack Intensity Factor

The CIF of the soil without fiber additive is much greater than the soil with fiber additives. The cracking behavior significantly affected by the change in the water content for natural soil (FC=0%) as shown in Figure 5.6. The observed CIF for soils with fiber additives was found zero for FC = 0.6 and 0.8% and indicated that the cracks were effectively suppressed. Small amount of cracks were found for FC of 0.2, 0.4, 1.0, and 1.2% respectively, which correspond to CIF range about 0.1 to 0.6%.

![Figure 5.6 Change in crack intensity factor with various fiber contents](image)

5.4 Acceptable Zone to Meet All Design Criteria

The contribution of fiber additive to the change of each parameter investigated was presented in Table 5.1. As expected, the use of fiber additive leads to an increased the value of each parameter tested in relation to the natural soil. Following Daniel and Wu (1993), an acceptable zone that meet with the design criteria proposed in this study could
be established by superposition. The AZ based on the unconfined compressive strength, tensile strength, cohesion, hydraulic conductivity, and crack intensity factor are all superimposed and presented in Figure 5.7. It can be seen from the superimposed plots that the CIF is the second most important parameter after hydraulic conductivity, which determines the acceptable value of FC. Once the requirement of CIF (i.e. CIF = 0 %) has satisfied, the condition of other parameter such as unconfined compressive strength, tensile strength and cohesion are also fulfilled. The overall AZ for the soil-fiber mixture can be constructed on the basis of the design criteria introduced in this study by using only hydraulic conductivity and CIF.

The result of this proposed method illustrate that it is possible to use the compacted soil-fiber mixture to adequate strength, low hydraulic conductivity and to simultaneously produce a compacted material with minimum crack potential in a landfill cover barrier layer.

Table 5.1 Influence of fiber contents on the engineering properties of the compacted soil-fiber mixtures

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum Dry Unit Weight</th>
<th>Unconfined Compressive Strength</th>
<th>Tensile Strength</th>
<th>Cohesion</th>
<th>Hydraulic Conductivity</th>
<th>Crack Intensity Factor</th>
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<tr>
<td>Symbol</td>
<td>( \gamma_{d_{max}} )</td>
<td>( \sigma_u )</td>
<td>( \sigma_T )</td>
<td>( c )</td>
<td>( k )</td>
<td>CIF</td>
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<table>
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<th>Fiber Content (%)</th>
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<th>Percent Change (%)</th>
<th>Influence with FC</th>
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<td>↑↑</td>
<td>100.0</td>
<td>↑↑</td>
<td>100.0</td>
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<td>↑↑</td>
<td>11.1</td>
<td>↑↑</td>
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<td>↑↑</td>
<td>242.9</td>
<td>↑↑</td>
<td>161.5</td>
<td>↑↑</td>
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</tr>
<tr>
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<td>3.6</td>
<td>↑↑</td>
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<td>187.8</td>
<td>↑↑</td>
<td>176.9</td>
<td>↑↑</td>
<td>97.1</td>
<td>↑↑</td>
<td>97.1</td>
<td>↑↑</td>
<td>97.1</td>
<td>0.0</td>
</tr>
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</table>

Notes: Influence with FC: ↑ increasing; ↔ no influence; ↓ decreasing
Figure 5.7  Overall acceptable zones for compacted soil-fiber mixtures

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unconfined Compressive Strength</th>
<th>Tensile Strength</th>
<th>Cohesion</th>
<th>Hydraulic Conductivity</th>
<th>Crack Intensity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>kN/m²</td>
<td>kN/m²</td>
<td>kN/m²</td>
<td>cm/s</td>
<td>%</td>
</tr>
<tr>
<td>45</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>1.0E-07</td>
</tr>
<tr>
<td>55</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>30</td>
<td>1.0E-06</td>
</tr>
<tr>
<td>65</td>
<td>15</td>
<td>20</td>
<td>30</td>
<td>40</td>
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<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>1.0E-04</td>
</tr>
<tr>
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<td>40</td>
<td>50</td>
<td>60</td>
<td>1.0E-03</td>
</tr>
<tr>
<td>0.01</td>
<td>0.02</td>
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<td>0.04</td>
<td>0.05</td>
<td>1.0E-02</td>
</tr>
<tr>
<td>0.02</td>
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<td>0.05</td>
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<td>1.0E-01</td>
</tr>
<tr>
<td>0.03</td>
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<td>1.0E-00</td>
</tr>
<tr>
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</tr>
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<td>0.10</td>
<td>0.11</td>
<td>0.12</td>
<td>1.0E-05</td>
</tr>
</tbody>
</table>
5.5 Summary

This chapter has described a design criterion for soil-fiber mixtures to be used as a landfill cover barrier layer. Using the method of superimposition, overall AZ was constructed to the soil specimens. Based on the results obtained in this study, the following conclusions can be made:

1. The superimposition method was used to develop the overall AZ with respect to the five design parameters, such as compaction characteristics, unconfined compressive strength, tensile strength, hydraulic conductivity, and crack intensity factor.

2. The compacted soil-fiber mixtures were found have a slight effect on the compaction characteristics. Therefore, the changes in compaction behavior of the soil due to fiber inclusion are considered insignificant.

3. The FC that increased unconfined compressive strength which satisfy the design criteria were found to be between 0.8 and 1.2%. Moreover, for tensile strength was found to be between 0.2 and 1.0%. The improvement in cohesion based on the criteria (more than 50%) was found for FC between 0.4 and 1.2%. The internal friction angle was not taken into consideration for design criteria in this study due to the internal friction angle was found slightly decreased with increasing in the FC of the soil specimens.

4. The hydraulic conductivity increased with increasing FC. The FC up to 1.2% maintained the hydraulic conductivity within acceptable level ($\leq 1 \times 10^{-5}$ cm/s) for non-hazardous waste.

5. The crack reduction significantly increased with fiber inclusion. The crack reductions approached 100% were found for FC between 0.6 and 0.8%. The CIF can be considered to be the second most significant factor after hydraulic conductivity controlling the shape of the overall AZ.

6. The optimum FC that was necessary to satisfy the condition of design criteria (overall AZ) introduced in this study was found to be 0.8%.

7. The results of this proposed design criteria illustrate that is possible to use the compacted soil-fiber mixture with increasing in the strength, low hydraulic conductivity, and to simultaneously produce a compacted material without cracking.
References


6.1 General

The cover system has been recognized as a critical component in landfills. The cover system separates reclaimed waste or containment material from the surface environment, restricts infiltration of water into the waste, and in some cases limits release of gas from waste. If the objective is prevention of pollution to ground water, then the main strategy is to minimize the water percolating through the cover system (USEPA, 1989). In the United States and most European countries, it has already been recognized that the installation of cover and bottom liner systems as a landfill containment facilities is an effective method of water interception for the prevention of leachate migration.

Alternative landfill covers are already in use in a variety of settings and have several potential benefits over the conventional landfill covers, while potentially being equally protective of human health and the environment. In addition, some researchers have documented that alternative final cover system can equal the performance of composite covers in some locations and can outperform conventional compacted clay cover in certain settings. Some of the benefits include, more readily available construction material, ease of construction, less complex quality assurance/quality control programs, increased long-term integrity, and stability (ITRC, 2003).
This chapter discussed and focused primarily on hydraulic barrier of cover systems. The alternative and innovative design of hydraulic barrier layer namely the multi-layer barrier layer was proposed. Furthermore, the water balance analysis was conducted to analyze the water interception performance of column test and predict the water storage capacity in the multi-layer barrier layer. After clarifying the performance of all parameters used, the overall performance of the innovative multi-layer barrier layer is discussed.

6.2 Conceptual Design

Covers placed over landfills are multi-component cover systems that are constructed directly on top of the waste shortly after a specific unit or cell has been filled to capacity. The common components within a final cover system are the erosion control layer, protection layer, drainage layer, hydraulic barrier layer, gas vent layer, and foundation layer. However, not all components are needed for all final covers. For example, a gas vent layer may be required for some covers but not others, depending upon whether the waste is producing gases that require collection and management. In addition, some of the layer may be combined. For instance, the gas collection layer can be combined as a single layer with the foundation layer (Daniel, 1995; Koerner and Daniel, 1997). Other important design issues related to the design of the final cover system include materials, desiccation cracking problem, landfill gas containment and control, settlement, erosion, long-term maintenance requirement, and slope stability.

6.2.1 Typical Cover System Design

When municipal solid waste (MSW) is filled to capacity, it is capped with a final cover that keeps out infiltration and keeps in gases and volatile components. The regulation dealing with final covers for municipal solid waste (MSW) recommended in the USEPA (1995) include the infiltration layer must be comprised of a minimum of 18 inches (450 mm) of earthen material that has permeability less than or equal to the permeability of any bottom liner system or natural subsoil present, or a permeability no greater than 1 x 10^{-5} cm/sec. The erosion layer must consist of a minimum of 6 inches (150 mm) of earthen material that is capable of sustaining native plant growth. Furthermore, the regulations permit the director of an approved state to approve an alternative final cover design that
includes an equivalent requirement. It should be noted, however, that cover regulations in other countries vary considerably from the preceding and from one another as well.

### 6.2.2 Alternative Landfill Cover Systems

Most landfill covers in U.S. must meet the minimum regulatory performance standards set forth under the EPA's Resource Conservation and Recovery Act (RCRA) in Subtitle D for municipal landfills (soil cover) and Subtitle C for hazardous waste landfills (compacted clay cover). Although Subtitles D and C describe particular cover designs in detail, landfill design engineers are not required to use them. The regulations allow the governing regulatory agency to consider and approve an alternative final cover as long as it meets general performance standards (Dwyer, 1998).

**Capillary Barrier**

This type of cover system consists of one or more layers of finer-grained soil overlying one or more layers or coarser-grained soil. At low degree of soil saturation, i.e. at high matric suction, the hydraulic conductivity of the coarser-grained soil is much less than that of the fine-grained soil. This is the reverse of the condition that occurs when the coarse-grained soil is at high degree of soil saturation. Figure 6.1 shows the relationship between hydraulic conductivity and matric suction. Field studies have suggested that capillary barriers can be used for restricting percolation in semiarid and arid climates (Nyhan et al., 1993; Stormont, 1995; Gee and Ward 1997; Nyhan et al., 1997). Capillary barriers either: (i) store water by increased moisture content in the fine-grained soil for subsequent evapotranspiration, or (ii) divert infiltrating water via unsaturated lateral flow in the fine-grained soil (above the soil interface). Sometimes a wicking layer (with intermediate characteristics to the coarse and fine-grained layers) is installed between the coarse and fine layers to convey lateral flow. At high degree of soil saturation in the coarse-grained soil, the capillary effect breaks down and percolation through the system can occur (Bonaparte and Yanful, 2001). Ankeny et al. (1997) proposed a concept referred to as a “dry barrier”, where a capillary break is constructed so that wind-driven air flow through the coarse layer removes any water that may infiltrate into the layer. Moreover, laboratory and field-scale testing of covers incorporating capillary breaks have
demonstrated their potential viability but included some failures (Stormont 1997; Dwyer 2001).

Evapotranspirative Cover System

One such alternative cover system, the evapotranspirative cover system is expected to have adequate long-term performance by using a soil layer placed in natural conditions and a vegetative cover consisting of a diverse native plant community. This type of cover system has also been developed primarily for use at arid and semi-arid sites. Evapotranspirative barriers are covers that consist of a thick layer of relatively fine-grained soil capable of supporting vegetation. Soil thickness can range from about 900 to 1800 mm (Zornberg and Caldwell, 1998). Evapotranspirative barrier exploit two characteristics of fine-grained soils: (a) significant soil water storage capacity, i.e. they can store a significant amount of water before gravity drainage; and (b) low hydraulic conductivity, even at high degrees of saturation. An evapotranspirative barrier must be sufficiently thick that changes in moisture content do not occur near its base, i.e. all

Figure 6.1   Soil-water characteristics curve for finer and coarser-grained soils in capillary barrier (Khire et al., 1999)
changes in soil water storage should occur in the upper portion of the barrier. Otherwise, percolation will occur. The required barrier thickness is a function of the frequency and intensity of the precipitation, the unsaturated hydraulic properties of the soil, the type of health of cover vegetation, and the rate at which water can be removed by evapotranspiration. Soil types used for construction of evapotranspirative barriers include silty sands, silts and clayey silts (Bonaparte and Yanful, 2001).

### 6.2.3 Design of Innovative Multi-layer Cover Barrier Layer

As municipal solid waste (MSW) decomposes, it produces a blend of several gases, which is primarily composed of methane (about 40 – 60%) and carbon dioxide (CO₂). A methane gas (CH₄) is a greenhouse gas and also poses explosion hazard if uncontrolled. The release of the methane gas to the atmosphere creates some global warming problems. According to the USEPA (1999a), the landfills are the dominant source of the methane emission, accounting approximately 37% of the United States total in 1997 as shown in Figure 6.2.

![Figure 6.2 Sources of United States methane emission in 1997](image)

Many factors determine the gases given off by decomposing organics compounds in the wastes at landfills. The generation of methane gas is controlled by the activity of anaerobic bacteria. The weather conditions have a large effect on the rate of gas generation in landfill. Increased temperature allows the bacteria to grow faster and increases gas generation. Moisture also allows the bacteria population to grow and this moisture can be from precipitation. Increased humidity also appeals to bacteria. Moreover, the frequent
rain and storms can cause a large increase in gas production.

In order to overcome the generation gas problem commonly encountered in landfill, the innovative multi-layer barrier cover layer is introduced. The design of multi-layer cover barrier layer is adapted from the design of the king ancient mound tomb which located in Fukuoka prefecture, Japan. The ancient tomb is covered by multi-layer surface made of clay and sand as shown in Figure 6.3. The structure of tomb was found that can provide the relatively constant temperature inside the tomb. Figure 6.4 shows the variation of temperature in different places which observed at the tomb. The benefit of the mound tomb structure indicated that the potential of application in the landfill cover system to suppress the gas generation in the post-closure landfill.

![Figure 6.3](image1)  Multi-layer surface of the king ancient mound tomb (adapted from report of the Education Commitee of Katsugawa town, 1994)

![Figure 6.4](image2)  Variation in temperature of the ancient mound tomb (adapted from report of the Education Commitee of Katsugawa town, 1994)
Moreover, the compacted soil layer with fiber additive (CSLF) was used as a material for multi-layer barrier layer. The percentage of fiber content used is 0.8%. The reason of using fiber additives due to the soil-fiber mixtures could effectively suppress the desiccation cracking during dry season as described in the previous chapter (see Chapter 4). Furthermore, the CSLFs were compacted with 50 cm in thickness and have a saturated hydraulic conductivity \((k)\) equal to \(6.2 \times 10^{-7}\) cm/s. A portion of sand lens (Toyoura sand) with cone shape is attached to the CSLF. The schematic structure of multi-layer barrier in cover system was shown in Figure 6.5.

![Figure 6.5 Schematic structure of multi-layer barrier layer in cover](image)

* CSLF = Compacted Soil Layer with Fiber*
6.3 Water Balance Analysis

6.3.1 Definition of Water Balance Analysis

One of the most important functions of a landfill cover is to limit or eliminate the production of leachate in underlying waste by minimizing or eliminating percolation of water through the cover. The analysis of water routing in covers is called water balance analysis. The reason of designers and regulators analyze water balance in covers may include one of the following: (1) to compare alternative design profiles and materials, (2) to understand how the cover will function and which water routing mechanism are most important, (3) to estimate flow rates so that components of the system can be sized properly, and (4) to estimate the amount of contaminated liquid that will be generated.

6.3.2 Water Balance Concept for Cover System

In order to evaluate the effectiveness of the cover systems and also design of the facilities for leachate treatment, it is essential to analyze the water balance in landfills, especially to predict quantity of water percolating into waste layer from the cover system (Khire et al., 1997). The potential pathways for water movement onto and through a cover are shown in Figure 6.6. The input of water is precipitation, and output is drainage (percolation) of water out of the cover. Within the cover, water can be stored, drained laterally, or be returned to the atmosphere by evapotranspiration. To conserve mass, the quantity of water that flows into the cover must equal the quantity of flow out of the cover plus the change in amount of water stored within the cover. This principle of conservation of mass is the basis for the term water balance.

Covers are usually designed to minimize the amount of percolation of water out the base of the cover. Water percolation is minimized by maximizing runoff, maximizing lateral drainage, maximizing evapotranspiration, and physically blocking downward infiltration of water by including one or more hydraulic barrier layers in the cover system.
Figure 6.6  Pathways or water movement in landfill closure cross section
In a water balance analysis, water is routed into and out of a system using a series of calculations that require conservation of water mass. A cover system water balance is expressed in terms of water inflows and outflows and storage changes for a unit area of the system over some arbitrary time interval as:

\[ P = R + ET + \Delta W_{\text{surface}} + \Delta W_{\text{foliage}} + \Delta W_{\text{soil}} + L + PERC \]  

(6.1)

where \( P \) is the precipitation (mm day\(^{-1}\)), \( R \) is the runoff (mm day\(^{-1}\)), \( ET \) is the evapotranspiration (mm day\(^{-1}\)), \( \Delta W_{\text{surface}} \) is the change in water storage at surface (mm day\(^{-1}\)), \( \Delta W_{\text{foliage}} \) is the change in water storage on plant foliage (mm day\(^{-1}\)), \( \Delta W_{\text{soil}} \) is the change in water storage in cover system soil (mm day\(^{-1}\)), \( L \) is the lateral drainage from internal drainage layer (mm day\(^{-1}\)), and \( PERC \) is the percolation through the cover system (mm day\(^{-1}\)). Equation 6.1 is cast above in a time unit of one day, any other time unit could equally well be used. Water balance calculations are performed for time intervals that may be shorter than one hour or longer than a year. The time interval to use is dependent on the purpose of the water balance analysis.

6.3.3 Method for Water Balance Analysis in Cover System

A variety of water balance methods are available to analyze and design cover systems. They range in complexity from relatively simple empirical correlations by hand to sophisticated computer-based finite difference and finite element models. In this section, the hand procedure is described. This procedure has also been recommended by Thornthwaite and Mather (1957), Fenn et al. (1975), and Kmet (1982).

One of the first decisions that must be made is whether to use hourly, daily, weekly, or monthly averages of precipitation. In this study, the water balance analysis was conducted based on hourly precipitation data. The precipitation data was collected based on the highest rainfall intensity (storm) in Saga prefecture, Japan. The ten maximum hourly precipitation data (1926 – 2006) in Saga Prefecture was presented in Table 6.1. The storm events can have a major impact on runoff, hourly averages of precipitation would be a logical time step. Experience indicates that during intense storms, the peak flow into
barrier layer can be significantly greater than predicted from daily or monthly averages of precipitation. Koerner and Daniel (1997) reported that the peak flow rate based on hourly storm data is nearly 40 times larger than the peak flow based on the daily precipitation values.

Based on the basic concept of water balance analysis as shown in Figure 6.5, the analysis for hourly average precipitation is obtained as:

\[ P = I + R \]  \hspace{1cm} (6.2)

and

\[ I = PERC + AET + \Delta Ws \]  \hspace{1cm} (6.3)

where \( P \) is the probable maximum precipitation (mm hr\(^{-1} \)), \( I \) is the infiltration, \( R \) is the runoff, \( PERC \) is the percolation, \( AET \) is the actual evapotranspiration, and \( \Delta Ws \) is the change in water stored in cover soil. The \( AET \) is negligible for an intense rainfall over a short period of time (e.g. a few hours). Therefore the following relationships result:

\[ P = PERC + \Delta Ws + R \]  \hspace{1cm} (6.4)

Table 6.1 Highest hourly precipitation data in Saga Prefecture, Japan

<table>
<thead>
<tr>
<th>Highest Hourly Precipitation</th>
<th>mm/hr</th>
<th>D / M / Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101.5</td>
<td>25 - 7 - 1937</td>
</tr>
<tr>
<td>2</td>
<td>72.3</td>
<td>25 - 6 - 1953</td>
</tr>
<tr>
<td>3</td>
<td>72</td>
<td>2 - 7 - 1990</td>
</tr>
<tr>
<td>4</td>
<td>71</td>
<td>27 - 7 - 1073</td>
</tr>
<tr>
<td>5</td>
<td>70.4</td>
<td>6 - 8 - 1950</td>
</tr>
<tr>
<td>6</td>
<td>69.5</td>
<td>31 - 8 - 1999</td>
</tr>
<tr>
<td>7</td>
<td>68.6</td>
<td>25 - 9 - 1954</td>
</tr>
<tr>
<td>8</td>
<td>64.5</td>
<td>13 - 9 - 1976</td>
</tr>
<tr>
<td>9</td>
<td>63.5</td>
<td>15 - 8 - 1970</td>
</tr>
<tr>
<td>10</td>
<td>63</td>
<td>10 - 9 - 1999</td>
</tr>
</tbody>
</table>
Runoff quantity \( (R) \) overflowing on the surface of a cover system estimated according to the following relationship (Koerner and Daniel, 1997):

\[
R = P \times C
\]  

(6.5)

where \( C \) is the surface runoff coefficient. Surface runoff coefficient \((C)\) is defined by the type of composed soil and the angle of the surface layer in the cover system. Typical runoff coefficient for completed landfill covers are given in Table 6.2. Runoff is one of the most difficult parameters to determine accurately because very little information is available on actual runoff rates from landfill covers. Two approaches are used for estimating the runoff coefficient. The simple approach is to estimate a value based on the type of soil and average angle of the slope which provided by Fenn et al. (1975). The procedure recommended by Schroeder et al. (1994) which is applicable for large storms and developed by plotting measured runoff in the stream versus rainfall. This method in determining of the runoff coefficient was adapted for measuring the runoff coefficient in this study.

### Table 6.2 Typical runoff coefficient (Inazumi, 2003)

<table>
<thead>
<tr>
<th>Type of soil</th>
<th>Slope (%)</th>
<th>Runoff coefficient (C)</th>
<th>With grass</th>
<th>Without grass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Range</td>
<td>Typical</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>2</td>
<td>0.05 - 0.10</td>
<td>0.06</td>
<td>0.06 - 0.14</td>
</tr>
<tr>
<td></td>
<td>3 - 6</td>
<td>0.10 - 0.15</td>
<td>0.12</td>
<td>0.14 - 0.24</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.15 - 0.20</td>
<td>0.17</td>
<td>0.20 - 0.30</td>
</tr>
<tr>
<td>Silty loam</td>
<td>2</td>
<td>0.12 - 0.17</td>
<td>0.14</td>
<td>0.25 - 0.35</td>
</tr>
<tr>
<td></td>
<td>3 - 6</td>
<td>0.17 - 0.25</td>
<td>0.22</td>
<td>0.35 - 0.45</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.25 - 0.36</td>
<td>0.30</td>
<td>0.45 - 0.55</td>
</tr>
<tr>
<td>Tight clay</td>
<td>2</td>
<td>0.22 - 0.33</td>
<td>0.25</td>
<td>0.45 - 0.55</td>
</tr>
<tr>
<td></td>
<td>3 - 6</td>
<td>0.30 - 0.40</td>
<td>0.35</td>
<td>0.55 - 0.65</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.40 - 0.50</td>
<td>0.45</td>
<td>0.65 - 0.75</td>
</tr>
</tbody>
</table>
6.4 Performance of Innovative Multi-Layer Cover Barrier Layer with Soil-Fiber Mixture

6.4.1 Model Column Test

Material Used

The materials used in this study are Akaboku soil and polypropylene (C\textsubscript{3}H\textsubscript{6}) fiber. The Akaboku soil was sampled from Kumamoto Prefecture, Kyushu Island, Japan. The hydraulic conductivity for Akaboku soil with \( FC = 0.8\% \) is \( 6.2 \times 10^{-7} \) cm/s. The soil samples were compacted at optimum moisture content (OMC) and \( \gamma_d \text{ max} \) using a standard Proctor compacter. The Toyoura sand (Japan standard sand) was used as a material for sand lens with hydraulic conductivity of \( 1.4 \times 10^{-2} \) cm/s. The sand lens was compacted at OMC and \( \gamma_d \text{ max} \) using a Harvard miniature compacter. Furthermore, the fiber used in this study as an additive material is polypropylene fiber (RCP17T) with 10mm length and 50 \( \mu \text{m} \) in diameter. The properties of the material used in this study are presented in the previous chapter (see Chapter 3). Moreover, the CSLF was used with \( FC = 0.8\% \).

Experimental Setup

Model column test was conducted to observe the performance of multi-layer cover barrier layer. The laboratory experiment was conducted in a plexyglas cyrcle column of which have a diameter of 20 cm and 150 cm in height. The column was provided with holes for collecting runoff and measure the volumetric water content. The column was also instrumented to collect the effluent water placed at the bottom of the column. Furthermore, the sand lenses (cone shape) which have 10 cm in diameter and 10 cm in height were installed inside the CSLF. The sand lens was design in model column test with 1:10 scale in horizontal and 1:1 scale in vertical length. Volumetric water contents were measured using Hydrosense moisture meter. The rainfall intensities were simulated with the modified rainfall simulator at various intensity, e.g. for 30 mm/hr, 50 mm/hr, and 100 mm/hr representing the normal, intermediate and heavy (storm) condition respectively. Figure 6.7 shows the schematic diagram of rainfall column test in this study. During the
observation the runoff, volumetric water content, and effluent water were periodically measure every hour.

Figure 6.7  Schematic diagram of equipment for column test
6.4.2 Water Interception Performance of Model Column Test

The evaluation of the performance of multi-layer barrier layer of rainwater interception was discussed in this section. The quantities of infiltrated water that pass through the surface layer into the barrier layer depend on the quantity of precipitation. Figure 6.8 shows the variations of water balance of multi-layer barrier layer with elapsed time (24 hours) for three different rainfall intensities. In general, the behavior of percolation and water stored in barrier layer are similar for all rainfall intensity applied. The quantity of water percolating from the barrier layer was found very small. The average percolation rate (over the study period) through barrier layer was found about 1.1 to 2 mm/hr, which equals approximately 1.1 to 2% of precipitation. The average individual percolation rate was less than 1.4 mm/hr for all rainfall intensity applied. Furthermore, the average quantity of water storage was varied in range between 10.3 and 13.3 % of precipitation. The average quantity of water interception of multi-layer barrier layer was found more than 85% of precipitation. However, the water interception capacity of cover system using sludge barrier layer was reported more than 95% (Inazumi, 2003).

Figure 6.8  Variation in water balance with elapsed time (24 hrs): (a) 30 mm/hr
Figure 6.8 Variation in water balance with elapsed time (24 hrs): (a) 50 mm/hr, and (c) 100 mm/hr.
Moreover, in figure 6.9 shows the variations of water balance of multi-layer barrier layer with elapsed time (168 hours) for three different rainfall intensities. Similar behavior was observed and shows that the behavior of percolation and water stored in barrier layer are similar for all rainfall intensity applied even for longer time observation. No significant change in water storage capacity and percolation up to seven days observation.

Figure 6.9  Variation in water balance with elapsed time (168 hrs): (a) 30 mm/hr
Figure 6.9 Variation in water balance with elapsed time (168 hrs): (b) 50 mm/hr and (c) 100 mm/hr.
The results also show that approximately 85% of the precipitation would be removed from the cover system as a surface runoff, and 15% would be infiltrated into the cover system in which approximately 13% stored in barrier layer. If the precipitation exceeds the infiltration capacity defined by saturated hydraulic conductivity of the cover system, the accumulated water quantity on the surface would be removed as surface runoff. The lower hydraulic conductivity ($1 \times 10^{-7}$ cm/s) is believed to be responsible for the low percolation rates of the multi-layer barrier layer (FC = 0.8%). This can be explained by Darcy’s rule, the quantity of water percolating from the barrier layer determined by the hydraulic conductivity and the hydraulic gradient. Since the hydraulic gradient for hourly precipitation assumes to be unity, the quantities of water percolating from the cover system with multi-layer barrier layer seem to depend on the hydraulic conductivity. It has been confirmed that the hydraulic conductivity is the critical elements for water interception performance in cover system. Inazumi (2003) reported similar result by using sludge material for barrier layer in cover system. Furthermore, it is indicated that the multi-layer barrier layer is able to effectively intercept the quantity of precipitation and store the infiltrated water to the barrier layer. The amount of water stored in the multi-layer barrier layer indicated that during the dry periods, the barrier layer could provide moisture to prevent the desiccation cracking problem. Moreover, the storage capacity is also believed that could provide humidity to keep the barrier layer temperature remained constant.

The variation in the volumetric moisture content of the multi-layer barrier showed an effect on the rainwater interception performance of the cover system. The distribution of volumetric water content for all rainfall intensity studied was shown in Figure 6.10. Volumetric water content measured at five depths, e.g. 2.5 cm (CSLF-A), 12.5 cm (sand lens-B), 22.5 cm (CSLF-C), 32.5 (sand lens-D), and 45 cm (CSLF-E). Increases in water content occur at the deeper area for both CSLF and sand lens. During the precipitation, the water content of CSLF and sand lens gradually increased due to the influx of precipitation. Benson et al. (1994) reported the similar trends of change in water content monitored in the field. Furthermore, the water content of the upper layer was highly dependent on the precipitations. The data shows that the surface layer (probe at 2.5 and 12.5 cm depth) experience the greatest fluctuation in water content, whereas the water content of the deeper barrier layer changes more gradually.
Figure 6.10  Variation in volumetric water content with different depth: (a) 30 mm/hr, (b) 50 mm/hr, and (c) 100 mm/hr.
6.4.3 Prediction of Water Storage in Cover Barrier Layer

The amount of water that a soil can store depends mainly on the type and density of the soil, as well as the thickness of soil layer. The field capacity of a soil is the highest water content at which water is retained in soil without gravity drainage. When the water content of soil rises above field capacity, water drains downward by gravity until field capacity is reached, at which point gravity drainage ceases (Koerner and Daniel, 1997). A relatively constant value of water stored was found in the barrier layer during the investigation (see Figure 6.8). It can be explained that the water storage has reached its field capacity. Therefore, the water still retained in the barrier layer. In fact, one standard way of measuring field capacity is to measure the relationship between water content and suction. However, for the purpose of estimating water balance in landfill covers, the use of the field capacity concept expressed independently of suction does not introduce unacceptable error because the assumption regarding field capacity is but one of many approximations. Often the field capacity is estimated rather than measured, in part because the water balance is usually performed as part of the design process before the cover is constructed, when the actual cover soil material is not yet known (Koerner and Daniel, 1997).

Predicting the effectiveness of water storage in the cover system over the long term presents a challenge, as there is usually not enough data available from long-term field monitoring. Stduying the relationship between water storage capacity and volumetric water content is useful in estimating the appropriate property that could be used in specific condition. The relationship between average volumetric water content ($\theta$) and water storage capacity ($W_s$) for compacted soil with fiber additive (CSLF) and sand lens could be calculated by using the relationship as shown in Figure 6.11 and 6.12. A good correlation exists, especially for CSLF material. The relationship shows that similar trend of all soil material was observed. It can be seen that the $\theta$ increased with increasing in $W_s$. The relationship between $\theta$ and $W_s$ for CSLF with rainfall intensity of 30 mm/hr is obtained as:

$$\theta = 0.7421 W_s + 9.3584$$  \hspace{1cm} (6.6)
The relationship between $\theta$ and $W_s$ for CSLF with rainfall intensity of 50 mm/hr is obtained as:

$$\theta = 0.4262 \ W_s + 8.2949 \quad (6.7)$$

The relationship between $\theta$ and $W_s$ for CSLF with rainfall intensity of 100 mm/hr is obtained as:

$$\theta = 0.7163 \ W_s + 7.5752 \quad (6.8)$$

Furthermore, the relationship between $\theta$ and $W_s$ for sand lens are presented in Figure 6.10, and the relationship for rainfall intensity of 30 mm/hr is obtained as:

$$\theta = 0.8354 \ W_s + 3.6071 \quad (6.9)$$

The relationship between $\theta$ and $W_s$ for sand lens with rainfall intensity of 50 mm/hr is obtained as:

$$\theta = 0.4264 \ W_s + 3.4594 \quad (6.10)$$

The relationship between $\theta$ and $W_s$ for sand lens with rainfall intensity of 100 mm/hr is obtained as:

$$\theta = 0.4525 \ W_s - 4.2347 \quad (6.11)$$

The interrelationships show a good correlation for all of the rainfall intensity applied. The equation obtained from this interrelationship can be used interchangeably to predict the values of $\theta$ and $W_s$. 
Figure 6.11   Relationship between $\theta$ and $W_s$ for CSLF: (a) $P = 30$ mm/hr, (b) $P = 50$ mm/hr, and (c) $P = 100$ mm/hr
Figure 6.12 Relationship between $\theta$ and $W_s$ for sand lens: (a) $P = 30$ mm/hr, (b) $P = 50$ mm/hr, and (c) $P = 100$ mm/hr

- (a) $P = 30$ mm/hr
  \[ \theta = 0.8354 \times W_s + 3.6071 \]
  \[ R^2 = 0.7805 \]

- (b) $P = 50$ mm/hr
  \[ \theta = 0.4264 \times W_s + 3.4594 \]
  \[ R^2 = 0.6719 \]

- (c) $P = 100$ mm/hr
  \[ \theta = 0.4525 \times W_s - 4.2347 \]
  \[ R^2 = 0.6317 \]
6.5 Estimation of the Hydraulic Conductivity Function based on the Soil-Water Characteristic Curve

The hydraulic conductivity function of an unsaturated soil can be predicted with sufficient accuracy for many engineering applications with knowledge of the saturated hydraulic conductivity and the soil-water characteristic curve. Several investigators have proposed empirical functions for predicting the hydraulic conductivity function (Huang et al. 1994). The soil-water characteristic curve equation developed by Fredlund et al. (1994) defines the water content-suction relationship over the entire suction range. This curve can be used to compute the hydraulic conductivity function, the relationship between hydraulic conductivity and soil suction.

6.5.1 Soil-Water Characteristic Curve

The soil-water characteristic curve, also referred to as the water retention curve, has played a dominant role in understanding the behavior of unsaturated soils in disciplines such as soil science, soil physics, agronomy and agriculture. As a consequence of the long history associated with the use of the soil-water characteristic curve, large amounts of information and experimental data are available from these disciplines. The soil-water characteristic curve is now recognized as one part of the water phase constitutive relationship in geotechnical engineering. The soil water characteristic curve is of greatest value in predicting unsaturated soil property functions. As a result, it is essential that the nature and theory behind the soil-water characteristic curve be well understood when implementing unsaturated soil mechanics.

The soil-water characteristic curve is a relationship between the amounts of water in the soil and the soil suction, or stress, on the soil. The water content of the soil is plotted as a function of suction. Suction is usually plotted on a logarithmic scale to accommodate the large range of suctions, approximately six orders of magnitude. Negative values cannot be plotted on a logarithmic scale, and as a result, suction is plotted as a positive value. The suction represents a negative pore water pressure in the soil. The amount of water in the soil, plotted arithmetically, is generally quantified in terms of volumetric water content ($\theta$).
but can also be expressed as gravimetric water content \((w)\), or degree of saturation \((S)\). Figure 6.13 shows the typical feature of a soil-water characteristic curve. Volumetric water content \((\theta)\) is defined as the ratio of the volume of water to the total volume of soil. Relationships can be written between the various volume-mass designations for water content. The relationship between volumetric water content \((\theta)\), and other variable is:

\[
\theta = \frac{S e}{1 + e} = S n
\] (6.12)

where \(e\) is the void ratio, \(S\) is the degree of saturation, and \(n\) is porosity. The relationship between \(\theta\) and \(w\), can be written as:

\[
\theta = w \gamma_d
\] (6.13)

where \(\gamma_d\) is the dry unit weight of the soil specimen.

Figure 6.13   A typical soil-water characteristic curve for predicting the hydraulic conductivity (adapted from Fredlund et al. 2000).
6.5.2 Experimental Approach of the Soil-Water Characteristic Curve

Material Used

The compacted soil-fiber mixture with FC = 0.8% was used for determine the soil-water characteristic curve. The geotechnical properties of material used is presented in previous chapter (see Chapter 3).

Filter Paper Technique Setup

Filter paper methods, which were first developed for agricultural and soil science applications, are relatively simple, low-cost, and reasonably accurate alternatives to many of the testing techniques described above. The American Society for Testing and Materials (ASTM) Standard D5298 describes calibration and test procedures for the measurements of either matric suction using the contact filter paper technique or total suction using non-contact filter paper technique. Fawcett and Collis-George (1967), McQueen and Miller (1968), Al-Khafaf and Hanks (1974), Hamblin (1981), Chandler and Gutierrez (1986), Houston et al. (1994), and Likos and Lu (2002) all provide additional discussion and analysis.

In this study non-contact filter paper technique was used in determining the total suction of the soil specimen. The non-contact technique estimate soil suction indirectly by measuring the amount of moisture transferred from an unsaturated soil specimen to an initially dry filter paper. The Whatman #42 type of filter paper was used in this study. A typically sized paper is circular with a 5.5 cm in diameter, weighing on the order of 0.2 g. Prior to non-contact testing, papers are calibrated by determining the relationship between equilibrium water content and relative humidity using salt solutions of known concentration, typically NaCl and KCl. The non-contact method has found greater applicability in geotechnical engineering practice. Figure 6.14 shows calibration curves according to ASTM Standard D5298 for Whatman #42 and Schleicher and Schuell #589 papers.
Figure 6.14  Calibration curves for Whatman #42 and Schleicher and Schuell #589 filter papers (ASTM D5298, ASTM 2000).

Results and Discussion

Figure 6.15 shows the soil-water characteristic curve for the compacted soil-fiber mixture with FC = 0.8%. The volumetric water content tends to decrease gradually with an increase in the total suction. Furthermore, an asymptotic tendency is observed at total suction levels higher than $10^4$ kPa. The water content declines significantly with increasing suction. It can be seen that the large increase in suction lead to relatively small changes in water content. This stage is referred to as the residual stage of saturation. There is a fraction of relatively immobile water in the pores of the soil at this stage, which has little or no contribution to the flow in pores (Huang, 1994). Water movement in this stage is primarily through vapor transport. The wetted area of contact is significantly reduced, compared to the saturated state, and soil suction is not significantly effective in contributing towards the shear strength of the soil. Moreover, the soil desaturates in the transition stage. The flow of water in the pores of the soil remains in the liquid phase as the applied suction increases. The water content in the soil is decline significantly with increasing suction. Flow occurs through progressively smaller size pores as the soil suction increases. The connectivity of the pores (voids) continues to reduce with
increasing values of suction, as the pathways for flow are reduced.

6.5.3 Unsaturated Hydraulic Conductivity

Statistical hydraulic conductivity models may be used to indirectly predict the hydraulic conductivity function from measurement or models of the soil-water characteristic curve. Childs and Collis-George (1950) proposed a statistical model to predict the hydraulic conductivity based on the random variation of pore sizes in a soil. This model was first modified by Marshall (1958), and further modified by Kunze et al. (1968). The calculations are performed by dividing the volumetric water content versus suction relationship into several water content increments. This is equivalent to integration along the volumetric water content axis. The following numerical integration procedure can be used along the soil-water characteristic curve to compute data points that can be best-fit to form the hydraulic conductivity function. The integration is carried out between the saturated volumetric water content and the volumetric water content under residual

![Soil-water characteristic curve for compacted soil-fiber mixture (FC = 0.8%)](image)

Figure 6.15  Soil-water characteristic curve for compacted soil-fiber mixture (FC = 0.8%)
conditions. Use the Jackson (1972) formalism to predict the unsaturated hydraulic conductivity function from the soil-water characteristic curve. The Jackson (1972) formalism may be written as:

\[
k(\theta_i) = k_s \left( \frac{\theta_i}{\theta_s} \right)^c \frac{\sum_{j=1}^{m} \left[ (2j+1-2i) h_j^{-2} \right]}{\sum_{j=1}^{m} \left[ (2j-1) h_j^{-2} \right]}\]

(6.14)

where \(k(\theta_i)\) is the unsaturated hydraulic conductivity at water content \(\theta_i\), \(k_s\) is the saturated hydraulic conductivity, \(m\) is the number of increments of \(\theta\) subdivided on the characteristic curve, \(h\) is the suction at the midpoint of each water content increment, and \(j\) and \(i\) are summation indices. The exponent \(c\) is a constant that can vary between 0 and 1.33 but is typically set equal to unity.

Based on the soil-water characteristic curve in Figure 6.15, the unsaturated hydraulic conductivity was determined by using Equation 6.14. The saturated hydraulic conductivity was determined independently (see in Chapter 3) as \(k = 6.2 \times 10^{-7}\) cm/s. The relationship between the unsaturated hydraulic conductivity and the volumetric water content is shown in Figure 6.16. Furthermore, the value of the unsaturated hydraulic conductivity is presented in Table 6.3. Initially, the unsaturated hydraulic conductivity slightly decreased in the higher level of volumetric water content. In the lower value of volumetric water content (e.g. < 15%), the unsaturated hydraulic conductivity significantly decreased in two orders of magnitude with a decreases in the volumetric water content from the initial condition to the drying state. Such a significant decrease in the unsaturated hydraulic conductivity for variations in the water content is firstly due to the removed water from the largest soil pores. According to the Hagen-Poiseuille law, implies that the passage of water through the smaller soil pores is more difficult than that through the larger pores. If the water content decreases, the refraction of the flow increases, and the waterway is lengthened. For unsaturated soil system, liquid flow occurs only within the liquid-filled pores. The unsaturated hydraulic conductivity function can thus be predicted if the relationship between the fluid-filled pore size and suction, that is, the soil-water characteristic curve is known (Lu and Likos, 2004).
Figure 6.16  Unsaturated hydraulic conductivity versus volumetric water content

Figure 6.17  Unsaturated hydraulic conductivity versus total suction
Figure 6.17 shows the relationship between unsaturated hydraulic conductivity and total suction. The unsaturated hydraulic conductivity, drops as the soil suction increases. It can be seen that, initially there is no significant changes in unsaturated hydraulic conductivity with increasing in the total suction. As the soil desaturate under increasing suction, the soil specimen more conductive to water due to the larger fraction of the silt’s smaller pores remain available to conduct water at increasingly large value of suction. However, the total suction higher than 1000 kPa, the unsaturated hydraulic conductivity dramatically decreased. This observation is a direct reflection of Young-Laplace equation and the capillary theory.

Moreover, using the relationship in Figure 6.15, the unsaturated hydraulic conductivity of the compacted soil-fiber mixture which is used in this study can be predicted. The initial average volumetric water content of the soil specimen is 15% which correlate to unsaturated hydraulic conductivity \( k(\theta_i) \) of 1.9 x 10^{-7} cm/s. This result indicated that the unsaturated hydraulic conductivity of the compacted soul-fiber mixture is lower than its saturated hydraulic conductivity.

### 6.6 Summary

This chapter describes the innovative design of barrier layer of cover system namely multi-layer barrier layer. The water balance analysis was conducted to evaluate the water interception of barrier layer proposed in study using model column test. The method to

### Table 6.3 Unsaturated hydraulic conductivity of soil-fiber mixture (FC=0.8%)

<table>
<thead>
<tr>
<th>No</th>
<th>( k_s ) (cm/s)</th>
<th>( i )</th>
<th>( j )</th>
<th>( \theta_s ) (%)</th>
<th>( \theta_i ) (%)</th>
<th>( A )</th>
<th>( B )</th>
<th>( k(\theta_i) ) (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.2 x 10^{-7}</td>
<td>1</td>
<td>1</td>
<td>0.270</td>
<td>0.270</td>
<td>1.23 x 10^{-5}</td>
<td>1.23 x 10^{-5}</td>
<td>6.2 x 10^{-7}</td>
</tr>
<tr>
<td>2</td>
<td>6.2 x 10^{-7}</td>
<td>2</td>
<td>2</td>
<td>0.270</td>
<td>0.267</td>
<td>1.22 x 10^{-5}</td>
<td>1.23 x 10^{-5}</td>
<td>6.1 x 10^{-7}</td>
</tr>
<tr>
<td>3</td>
<td>6.2 x 10^{-7}</td>
<td>3</td>
<td>3</td>
<td>0.270</td>
<td>0.266</td>
<td>1.20 x 10^{-5}</td>
<td>1.23 x 10^{-5}</td>
<td>6.0 x 10^{-7}</td>
</tr>
<tr>
<td>4</td>
<td>6.2 x 10^{-7}</td>
<td>4</td>
<td>4</td>
<td>0.270</td>
<td>0.230</td>
<td>1.16 x 10^{-5}</td>
<td>1.23 x 10^{-5}</td>
<td>5.0 x 10^{-7}</td>
</tr>
<tr>
<td>5</td>
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<td>5</td>
<td>0.270</td>
<td>0.218</td>
<td>1.07 x 10^{-5}</td>
<td>1.23 x 10^{-5}</td>
<td>4.4 x 10^{-7}</td>
</tr>
<tr>
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<td>6</td>
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<td>9.32 x 10^{-6}</td>
<td>1.23 x 10^{-5}</td>
<td>3.3 x 10^{-7}</td>
</tr>
<tr>
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<td>7</td>
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<td>6.92 x 10^{-6}</td>
<td>1.23 x 10^{-5}</td>
<td>2.1 x 10^{-7}</td>
</tr>
<tr>
<td>8</td>
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<td>8</td>
<td>8</td>
<td>0.270</td>
<td>0.111</td>
<td>2.23 x 10^{-6}</td>
<td>1.23 x 10^{-5}</td>
<td>4.6 x 10^{-8}</td>
</tr>
</tbody>
</table>

Note: A: \( \sum_{j=1}^{n} [(2j+1-2i)h_j^{-2}] \) \quad B: \( \sum_{j=1}^{n} [(2j-1)h_j^{-2}] \)
predict the relationship between volumetric water content and water storage capacity was also conducted. From the results and analyses of the laboratory column test, the following conclusions can be made:

1. The evaluation on the water interception performance of multi-layer barrier layer indicated that the average quantity of the water percolating is less than 2 mm/hr, which equals approximately 2% of the total precipitation applied. More than 85% of the precipitation could be intercepted by the multi-layer barrier layer as a surface runoff. It is indicated that the barrier layer effectively intercept the precipitation.

2. The barrier layer also appeared effectively to store water. Trends in water storage were similar for all rainfall intensity applied. The average water storage capacity for the multi-layer barrier layer was 13 mm, which equal approximately 13% of the precipitation. The amount of water stored in the multi-layer barrier layer indicated that during the dry periods, the barrier layer could provide moisture to prevent the desiccation cracking problem. Moreover, the water stored is also believed that could provide humidity to keep the barrier layer temperature remained constant.

3. The variation in the volumetric moisture content of the multi-layer barrier showed an effect on the rainwater interception performance of the cover system. Increases in water content occur at the deeper area for both CSLF and sand lens. During the precipitation, the water content of CSLF and sand lens gradually increased due to the influx of precipitation.

4. A relationship has been made between volumetric water content and water storage capacity obtained from column test. The relationship trends were generally similar for all rainfall intensity. A good correlation exists, especially for CSLF material. The interrelationships show a good correlation for all of the rainfall intensity applied. The equation obtained from this interrelationship can be used interchangeably to predict the values of $\theta$ and $W_s$.

5. The unsaturated hydraulic conductivity decreases with decreasing in the water content. This can be explained due to the soil-pore size distribution. Moreover, the unsaturated hydraulic conductivity can be predicted by using the relationship between unsaturated hydraulic conductivity and volumetric water content which presented in this chapter.
References


7.1 General

This study comprised mainly of three parts. The first part consists of Chapter 3 and 4 and presented the evaluation of the geotechnical properties of soil-fiber mixtures as a potential material for landfill cover system. Also, investigation on the desiccation cracking was conducted through a laboratory testing program. The second part (Chapter 5) discussed the design criteria of multi-layer barrier layer in cover system. This design criterion was proposed as an alternative method to design a barrier layer cover system using soil-fiber mixture. The last part (Chapter 6) analyzed the design and performance of multi-layer cover barrier system by conducting water balance analysis and predicts the water storage capacity of multi-layer barrier layer.

The study was undertaken in an attempt to accomplish the objectives include (1) evaluating the geotechnical properties and desiccation behavior of soil-fiber mixtures, (2) to proposed the design criteria of soil-fiber mixtures potentially used as a material for multi-layer cover barrier system, and (3) to investigate the performance of multi-layer cover barrier layer on rain water interception. Recommendations are outlined in terms of the needs for further research and the guidelines for design and construction. The main conclusions are summarized in following section.
7.2 Main Conclusions

1. The potential of using soil-fiber mixtures as a material for landfill cover barrier layer is evaluated by its geotechnical properties. Various geotechnical properties include compaction characteristics, compressive strength, tensile strength, shear strength, and hydraulic conductivity were evaluated. The contribution of fiber to the compaction characteristics (i.e. maximum dry unit weight) increases with increasing fiber contents. The fiber inclusion increased the compressive strength, ductility, and decreased the loss of the post-peak strength. With the inclusion of fibers, the energy absorbing capacity increases, resulting in higher ductility in the post-peak region. Furthermore, the inclusion of fibers increased the tensile strength of the soil-fiber mixtures. This is mainly due to the increase in the adhesion force as the surface contact area between the soil and fibers increase by increasing the fiber content. The highest compressive and tensile strength of soil-fiber mixtures occurred at the highest dry density of the soil specimen due to the rearrangement and dense packing of the particles by inclusion of fibers. Moreover, the shear strength of the compacted soil-fiber mixture increased with the fiber inclusion and was found that the improvement of shear strength mainly controlled by the cohesion. Finally, the hydraulic conductivity of soil-fiber mixtures increased with increasing fiber content. Significant improvements in the mechanical behavior of the soil-fiber mixtures indicate that there is some potential for the use of fibers additives in engineering practice (i.e. landfill cover barrier material).

2. The improved soil-fiber mixtures enhance the beneficial changes in the engineering properties of the Akaboku soil as discussed in previous part of this thesis (i.e. compaction characteristics, volumetric shrinkage strain, and the crack intensity factor). During the desiccation process, the volumetric shrinkage developed in the compacted Akaboku soil with and without fiber additives and substantially controlled by water content. The shrinkage limit increased significantly with the inclusion of fibers. The elevated shrinkage limit of the soil with fiber additives would suppress the volumetric shrinkage, since the higher water content of the soil-fiber mixtures may easily reach its shrinkage limit during desiccation process. With an increasing in the fiber content, the volumetric shrinkage strain decreased. The behavior of soil with and without fiber additives in the desiccation crack test would be only due to the fiber inclusions.
Fiber inclusion increased the volumetric shrinkage strain reduction significantly. The volumetric shrinkage strain decreased approximately 51% within the range of fiber contents used in this study. With the fiber additives, crack was significantly suppressed. The CIF decreased with increasing in the fiber content. This is mainly due to the interaction of soil particles and fibers, which enhanced the resistance against crack. This desiccation crack test suggests the potential application of the fiber additives to soils as an available method to suppress desiccation cracks commonly encountered in landfill cover system.

3. The superimposition method was used to develop the overall AZ with respect to the five design parameters, such as compaction characteristics, unconfined compressive strength, tensile strength, cohesion, hydraulic conductivity, and crack intensity factor. The compacted soil-fiber mixtures were found have a slight effect on the compaction characteristics. Therefore, the changes in compaction behavior of the soil due to fiber inclusion are considered insignificant. The FC that increased unconfined compressive strength which satisfy the design criteria were found to be between 0.8 and 1.2%. Moreover, for tensile strength was found to be between 0.2 and 1.0%. The improvement in cohesion based on the criteria (more than 50%) was found for FC between 0.4 and 1.2%. The internal friction angle was not taken into consideration for design criteria in this study due to the internal friction angle was found slightly decreased with increasing in the FC of the soil specimens. The hydraulic conductivity increased with increasing FC. The FC up to 1.2% maintained the hydraulic conductivity within acceptable level ($\leq 1 \times 10^{-5}$ cm/s) for non-hazardous waste and municipal solid waste (MSW). The crack reduction significantly increased with fiber inclusion. The crack reductions approached 100% were found for FC between 0.6 and 0.8%. The CIF can be considered to be the second most significant factor after hydraulic conductivity controlling the shape of the overall AZ. The optimum FC that was necessary to satisfy the condition of design criteria (overall AZ) introduced in this study was found to be 0.8%. The results of this proposed design criteria illustrate that is possible to use the compacted soil-fiber mixture with increasing in the strength, low hydraulic conductivity, and to simultaneously produce a compacted material without cracking.
4. The evaluation on the water interception performance of multi-layer barrier layer indicated that the average quantity of the water percolating is less than 2 mm/hr, which equals approximately 2% of the total precipitation applied. More than 85% of the precipitation could be intercepted by the multi-layer barrier layer as a surface runoff. It is indicated that the barrier layer could effectively intercept the precipitation. Furthermore, the barrier layer also appeared effectively to store water. Trends in water storage were similar for all rainfall intensity applied. The average water storage capacity for the multi-layer barrier layer was 13 mm, which equal approximately 13% of the precipitation. The amount of water stored in the multi-layer barrier layer indicated that during the dry periods, the barrier layer could provide moisture to prevent the desiccation cracking problem. Moreover, the water stored is also believed that could provide humidity to keep the barrier layer temperature remained constant. Moreover, the variation in the volumetric moisture content of the multi-layer barrier showed an effect on the rainwater interception performance of the cover system. Increases in water content occur at the deeper area for both CSLF and sand lens. During the precipitation, the water content of CSLF and sand lens gradually increased due to the influx of precipitation. A relationship has been made between volumetric water content and water storage capacity obtained from column test. The relationship trends were generally similar for all rainfall intensity. A good correlation exists, especially for CSLF material. The interrelationships show a good correlation for all of the rainfall intensity applied. The equation obtained from this interrelationship can be used interchangeably to predict the values of $\theta$ and $W_s$. Significant intercept behavior of the barrier layer in this study indicate that there is some potential for the use of multi-layer barrier layer in landfill cover system.

5. The unsaturated hydraulic conductivity of the soil-fiber mixture was determined by using the soil-water characteristic curve. The unsaturated hydraulic conductivity decreases with decreasing in the water content. This can be explained due to the soil-pore size distribution and a direct reflection of capillary theory. Moreover, an attempt was made to correlate the unsaturated hydraulic conductivity and volumetric water content in order to predict the relationship of those parameters. It can be applied for engineering practical purpose in designing the compacted soil-fiber mixtures as material for landfill barrier layer.
7.3 Recommendations for Further Research

1. Evaluation on the geotechnical properties of soil-fiber mixtures was conducted in this study. In order to study the effect of fiber length on the geotechnical properties of the soil-fiber mixtures, several fiber lengths could be utilized. Evaluation on the effect of fiber length would be very useful in determining the optimum length of fiber which has the highest improvement in the geotechnical properties of soil-fiber mixtures.

2. Since there is a limitation was found in the small size of soil specimen such as a large lateral deformation, a bigger size mold of the improvement method was proposed. The preliminary study using a natural soil was used in the improvement method of the desiccation crack test. However, the soil with fiber additives should be used in the improvement desiccation crack test to investigate the behavior of soil-fiber mixtures with bigger mold.

3. The design criteria based on the fiber content was introduced in this paper. This will provide the practical method of predicting the optimum fiber content in which meet with all design parameters used. However, other study based on the compaction control criteria is needed in order to compare and examine the efficiency of the design method used.

4. This study focuses on the performance of barrier layer as a part of the entire system of landfill cover. However, the investigation on the performance of entire cover system should be conducted in order to evaluate the integrity of the final cover system.

5. The barrier layer column test was simulated in only one condition of weather (heavy rainfall). The investigation based on the wet and dry cycles are needed in order to study the behavior of the parameters (i.e. water storage capacity and hydraulic conductivity) in barrier layer.

6. Since land reuse is an important consideration in landfill cover design, the analysis of slope stability, bearing capacity, and also evaluation of subsidence (settlement) should be conducted.
7. Currently the greatest research need is to collect long-term field data regarding physical and hydrological performance of final covers. Only limited numbers of field-scale studies have been conducted. The great reliance placed on final covers to protect the environment warrants a more thorough understanding of their performance and limitations. Other studies on the performance of cover systems are needed in many countries, including Japan.
Appendix

Photo A1.1  Unconfined compression test apparatus

Photo A1.2  Tensile test apparatus
Photo A1.3  Direct shear test apparatus

Photo A1.4  Hydraulic conductivity test apparatus
Desiccation crack test

Max. crack depth measurement

Deformation measurement

Weight measurement

Wind simulation by fan

Diameter measurement

Maximum crack depth measurement

Figure 3.7. Desiccation crack test

Photo A1.5  Desiccation crack test

Digital camera

50 cm

10 cm

30 cm

Photo A1.6  The surficial cracks were monitored by photographs with digital camera
Photo A1.7  Multi-layer column test apparatus

Photo A1.8  Hydrosense moisture meter
Figure A1. 9  High precision balance

Figure A1. 10  Sample curing in filter paper method
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