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

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ABSTRACT: The design criteria were introduced in this paper to design a landfill cover barrier layer using the compacted soil-fiber mixture for the future application (i.e. park, residential, etc.). Polypropylene (C_3H_6) fiber was used as an additive material for soil samples. The soil specimens compacted under the conditions of maximum dry density and optimum water content. In this study, the design objective in using the compacted soil-fiber mixture is to determine the range of fiber content (i.e. 0.0% - 1.2%) within which the soil specimens will have adequate compaction characteristics, compressive and tensile strength, minimum amount of cracking, and low hydraulic conductivity. It is found that the fiber content that maximized the maximum dry density was considered insignificant. Fiber content in excess of 0.8% showed significant increase in the unconfined compressive strength. The tensile strength significantly increased for soil specimens exceeding 0.2% of fiber content. An acceptable limiting value of the crack intensity factor to prevent desiccation cracking for soil specimen was found between 0.6 and 0.8% of fiber content. Moreover, the fiber contents up to 1.2% maintained the hydraulic conductivity within acceptable levels. As a result, the optimum fiber content that was necessary to meet the overall acceptable zones based on the parameter design investigated in this study was found and reported in this study.

Keywords: Design criteria, fiber additive, compacted soil, landfill cover barrier.

BACKGROUND

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; Harianto et al. 2008).

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 are not well established.

In this study, the criteria in order to design a landfill cover barrier layer using soil-fiber mixture material is proposed to 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 (≤ 1.0×10^{-5} cm/sec), have a suitable mechanical properties

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for structural integrity, and resistant to cracks due to desiccation.

MATERIALS AND TEST METHODS

The soil specimen (Akaboku soil) was locally collected from mountainous area, Kumamoto Prefecture, Kyushu Island, Japan. The Akaboku soil is categorized as a halloysite in clay mineral characteristics. The series of test were carried out for index properties, standard proctor compaction, unconfined compression test, tensile test, volumetric shrinkage test and hydraulic conductivity test. The soil specimen was kept in box under room conditions (25 ±2 ^{o}C, 50 ± 1 % relative humidity) prior to testing. The basic properties of soil such as grain size analysis, specific gravity of soil solids and Atterberg limits (liquid limit, plastic limit and shrinkage limit) were determined according to standard practice the American Society of Testing Materials (ASTM) D422-63, D854-58, D4318-00, and D427-61. The basic properties of the Akaboku soil are shown in Table 1.

Table 1 Basic properties of Akaboku soil

Properties	Values
Specific gravity, Gs	2.59
Consistency limit :	
Liquid limit, w_L (%)	162.0
Plastic limit, w_P (%)	81.7
Shrinkage limit, w_S (%)	48.9
Plasticity index, PI (%)	80.3
Grain size analysis :	
Sand (%)	35
Silt (%)	52
Clay (%)	13

The type of polypropylene fiber used in this study is RCP17T with 10 mm in length and 50 μm in diameter. The summary of the properties of polypropylene fiber are shown in Table 2.

Table 2 Properties of Polypropylene fiber

Properties	Value
Specific gravity	0.91
Fineness (dtex)[1]	15-19
Tensile strength (MPa)	2.0 - 6.0
Elongation at break (%)	70 - 150
Melt point (^{o}C)	160

[1]dtex = 10μg/cm

The mixing procedure in the making of sample was as follows. The soil was slight air dried to bring water content below the measured optimum moisture content (OMC). The soil retrieved in its in-situ state was above its OMC, therefore it was necessary to dry the soil first. The dry soil grinded and run the sample through a No. 10 sieves. The weight of fibers calculated based on dry weight to be added to the soil sample, and bring dry soil sample to desired percentage of OMC. The soil and fiber were mixed for 5 minutes at low speed (1430 rpm) and additional 2.5 minutes at high speed (1720 rpm). The soil sample was mixed at various percentages of fiber additives of 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2% respectively.

The standard proctor compaction test (ASTM D698-70) was conducted to determine initial compaction characteristics of the soil specimen. Compaction energy was equal to the compaction energy used in standard Proctor compaction tests, 593 kJm^{-3}. The unconfined compression test (ASTM D2166-66) was conducted for obtaining the compressive strength of the soil samples. The soil samples were compacted at OMC and maximum dry unit weight ($\gamma_{d\ max}$) using a Harvard miniature compacter.

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 $\gamma_{d\ max}$ using a standard Proctor compacter. 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 schematic diagram for laboratory modified indirect tensile apparatus is shown in Fig. 1.

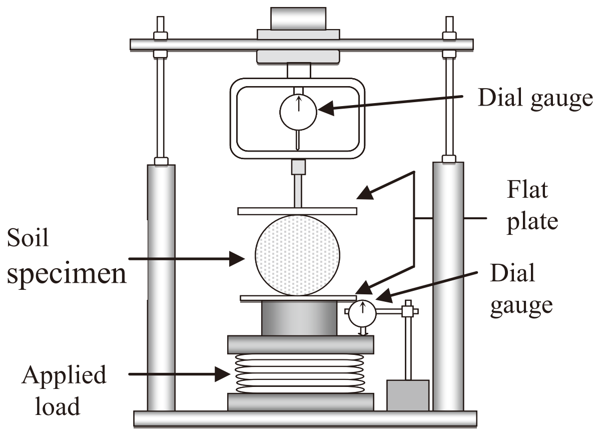

Fig. 1 Schematic of the modified indirect tensile apparatus

The tensile strength (σ_T) value was determined based on the following equation:

$$\sigma_T = {2P}/{\pi dl} \quad (1)$$

where P is the applied force, d and l represent specimen diameter and thickness.

Moreover, to evaluate the permeability of soil-fiber mixtures, the hydraulic conductivity test was conducted in this study. The 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 specimens were prepared cylindrical in 12.74 cm in height and 10 cm in diameter. For all specimens, the hydraulic gradient (i) was set to 24 and confining stress of 60 kPa was applied.

For the desiccation crack test, soil specimens were prepared with 30 cm in diameter and 10 cm in height. The soil specimens were prepared by compaction under the conditions of maximum dry density and OMC. 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) as shown in Fig 2. The drying process was conducted for a period of approximately 30 days. The surficial dimensions of cracks were monitored during the tests. 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. Crack Intensity Factor (CIF) was used as a parameter to evaluate the magnitude of desiccation cracks developed in the soils, expressed by:

$$\text{CIF} = {A_C}/{A_T} \quad (2)$$

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. 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. In this study, the crack depth exceeding 2 mm was found at the crack width greater than 0.5 mm. The CIF was determined at the end of the observation for both natural and soil-fiber mixtures.

In this study, the parameters for design of soil-fiber mixtures as a material for covers include compaction characteristics, unconfined compressive strength, tensile strength. However, for the hydraulic conductivity, the

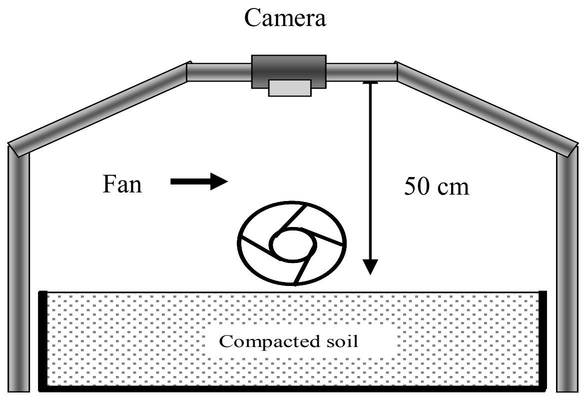

Fig. 2 Desiccation crack test setup

value should be less or equal to 1 x 10^{-5} cm/s (non-hazardous waste). 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 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 fiber content (FC) meets the design criterion. Using the method of superimposition, overall AZ was constructed to the soil specimens.

RESULTS AND DISCUSSIONS

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, minimum hydraulic conductivity, and minimum amount of cracking. The value should maximize the benefits of fiber inclusion in terms of all parameters mentioned previously.

Compaction Behavior of Tested Materials

The relationship of maximum dry unit weight ($\gamma_{d\ max}$) and FC are shown in Fig.3. 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 $\gamma_{d\ max}$ was obtained in the FC = 1.0%, which increase about 11% higher than that of the soil without fiber additives. 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 %, γ_{dmax} 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, γ_{dmax} decreased. However, values of the $\gamma_{d\ max}$ for each FC investigated fall within very narrow ranges and the variations in the $\gamma_{d\ max}$ are found less than 50%, which is considered insignificant.

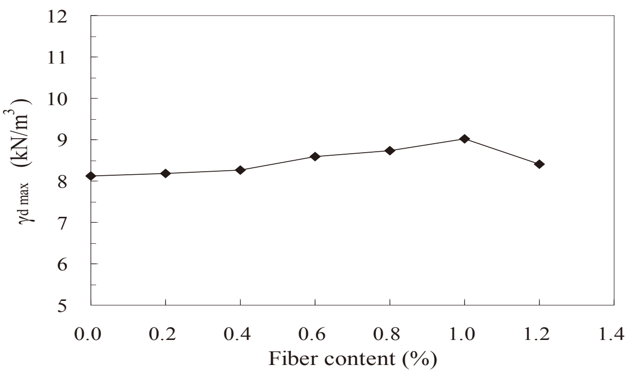

Fig. 3 Change in $\gamma_{d\ max}$ with various fiber

Effect of Fiber on Compressive Strength of Soil

Fig. 4 shows variation of the unconfined compressive strength (q_u) with various FC. The unconfined compressive strength 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%. Addition of fibers increased the peak stress and ductility of the soil specimen. 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. 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. Moreover, it can be seen that for FC = 0.8 - 1.2% were found to meet the design criterion. The AZ as shown in Fig. 4 indicates portion on the figure plane in which the q_u values increased equal or more than 50% compare to the natural soil.

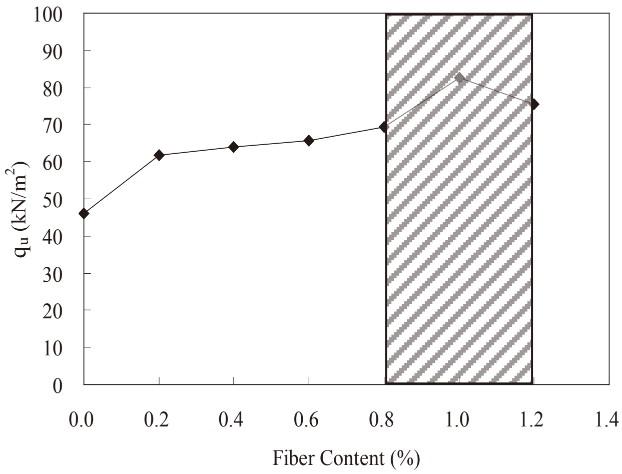

Fig. 4 Acceptable zone based on unconfined compressive strength consideration

Tensile Strength of Tested Materials

Similar relationship was also obtained for tensile strength with various FC as shown in Fig. 5. The value of tensile strength generally increased up to FC = 1.0% and then decreased of FC = 1.2%. Initially σ_T increased up to FC = 1.0% and decreased for FC = 1.2%. The results indicated that for the FC used, the value of σ_T varied between 10 (FC = 0%) and 35 kN/m^2 (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 σ_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. However, the

FC = 0.4 to 1.2% were found to meet the design condition. The AZ was determined based on the procedures in the previous section.

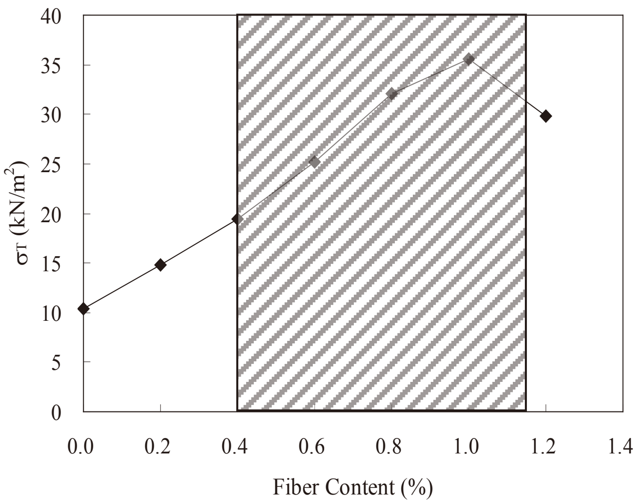

Fig. 5 Acceptable zone based on tensile strength consideration

Permeability Values

The most important parameter for landfill cover barrier applications can be evaluated by using 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). The relationship between hydraulic conductivity and FC is shown in Fig. 6. The slight decreased of hydraulic conductivity found for FC = 0 to 0.2 % and increased for higher FC. The increase in hydraulic conductivity was most significant for FC exceeding 0.8% which is 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) ≤ 1 x 10^{-5} cm/s. In this study, fiber contents up to 1.2% maintained the hydraulic conductivity 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.

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 Fig. 7. The observed CIF for soils with fiber additives was found

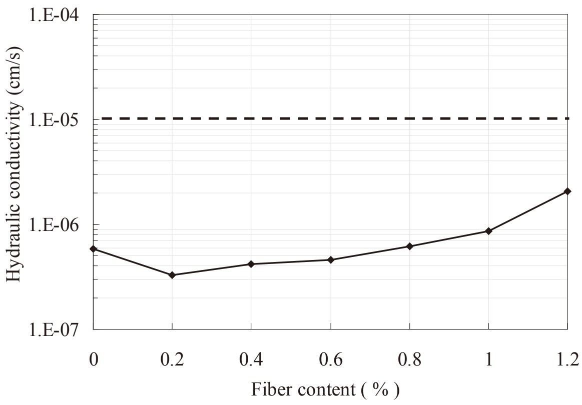

Fig. 6 Change in hydraulic conductivity with various fiber contents

zero for FC = 0.6 and 0.8%. 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%. 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. However, 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% . 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 during drying period, 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.

The contribution of fiber additive to the change of each parameter investigated was presented in Table 3.

As expected, the use of fiber additive leads to an increased the value of each parameter tested in relation to the natural soil.

Design Overall Acceptable Zones

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, hydraulic conductivity, and crack intensity factor are all superimposed and presented in Fig. 8. It can be seen from the superimposed plots that the CIF is the 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 and tensile strength are also fulfilled.

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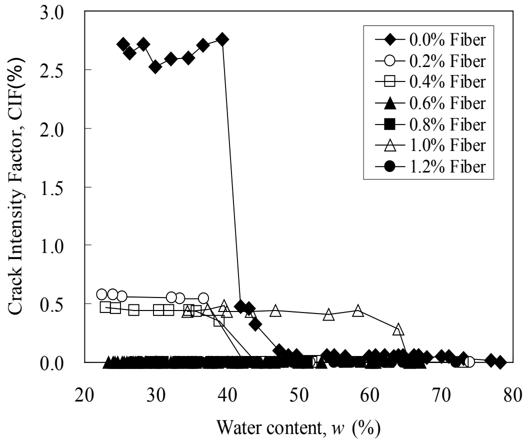

Fig. 7 Crack intensity factor for various fiber contents

Table 3 Influence of various fiber contents on the engineering properties of the compacted soil-fiber mixtures

Parameter	Maximum Dry Unit Weight		Unconfined Compressive Strength		Tensile Strength		Hydraulic Conductivity	Crack Intensity Factor	
Symbol	$\gamma_{d\,max}$		q_u		σ_T		k	CIF	
Fiber Content (%)	Influence with FC	Percent Change (%)	Influence with FC	Percent Change (%)	Influence with FC	Percent Change (%)	Influence with FC	Influence with FC	Percent Reduction (%)
0.0	↔	0.0	↔	0.0	↔	0.0	↔	↔	0.0
0.2		0.7		34.3		42.9			78.9
0.4		1.7		39.0		87.8			83.6
0.6		5.5		42.6		143.3			100.0
0.8		7.4		51.0		209.4			100.0
1.0		11.1		79.4		242.9			84.7
1.2		3.6		64.1		187.8			97.1

In this study, the criteria in order to design a landfill cover barrier layer using soil-fiber mixture material provide the minimum design requirement for landfill the minimum design requirement for landfill cover barrier system. Therefore, the thickness can be reduced up to 40% and effect to the lower cost in constructing the proposed cover system.

CONCLUSIONS

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 with 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%.

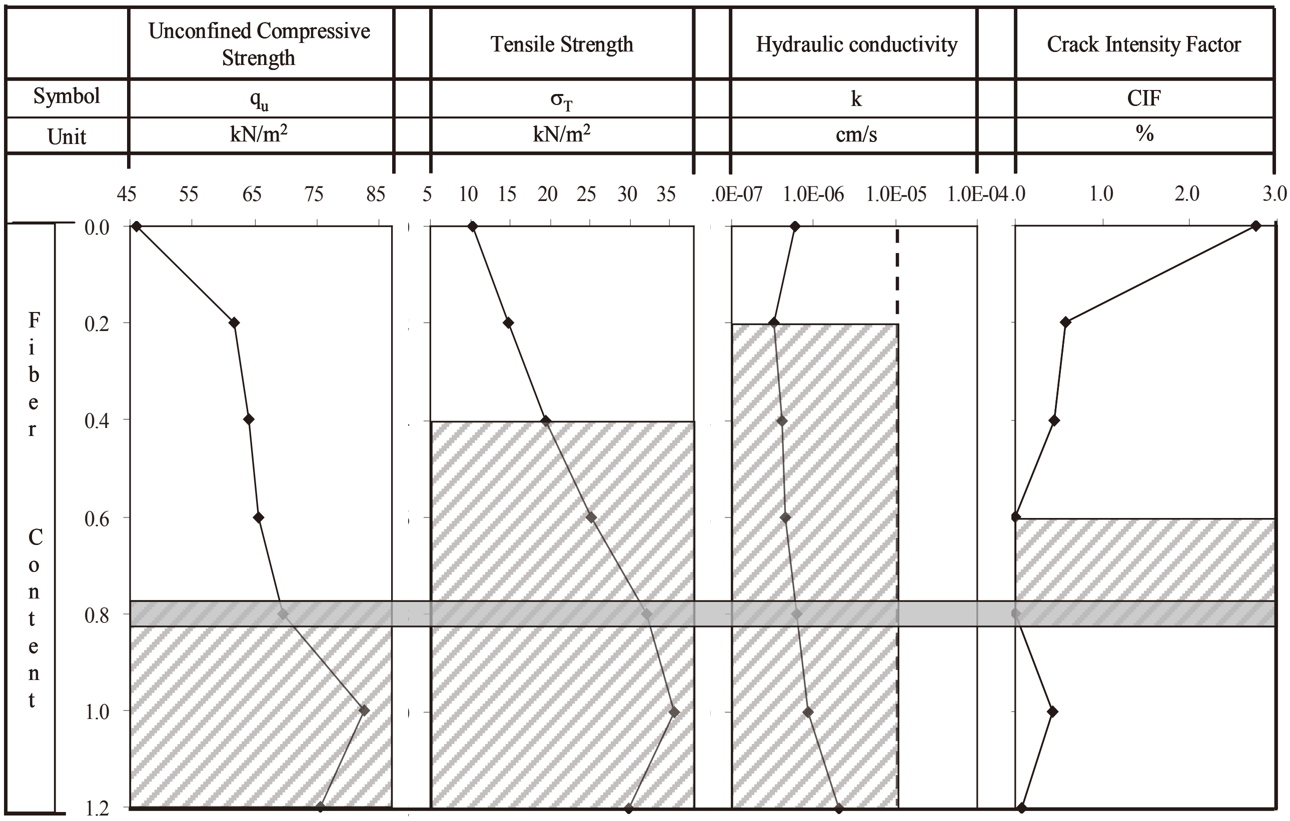

Fig. 8 Overall acceptable zones for the compacted soil-fiber mixtures

4. The FC up to 1.2% maintained the hydraulic conductivity within acceptable level (≤ 1 x 10^{-5} cm/s) for non-hazardous waste.
5. The crack reduction significantly increased with the fiber inclusion. The crack reductions approached 100% were found for FC between 0.6 and 0.8%.
6. The optimum FC that was necessary to satisfy the condition of design criteria (overall AZ) was found to be 0.8%.
7. The design criteria which is proposed in this study shows that is possible to use the compacted soil-fiber mixture as a material for landfill cover barrier system in increasing the strength, low hydraulic conductivity and simultaneously produce a compacted material without cracking.

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REFERENCES

ASTM D2166-66 (2000). Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, Annual Book of ASTM Standards, ASTM Int., West Conshohocken, PA.

ASTM D2434-68 (1994). Standard Test Method for Permeability of Granular Soils, Annual Book of ASTM Standards, ASTM Int., West Conshohocken, PA.

ASTM D422-63 (2002). Standard Test Method for Particle-Size Analysis of Soils, Annual Book of ASTM Standards, ASTM Int., West Conshohocken, PA.

ASTM D427-61 (1989). Standard Test Method for Shrinkage Limit of Soil Mixtures, Annual Book of ASTM Standards, ASTM Int., West Conshohocken, PA.

ASTM D4318-00 (2000). Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils, Annual Book of ASTM Standards, ASTM Int., West Conshohocken, PA.

ASTM D698-70 (2000). Standard Test Method for Soil Compaction, Annual Book of ASTM Standards, ASTM Int., West Conshohocken, PA.

ASTM D854-00 (2000). Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer, Annual Book of ASTM Standards, ASTM Int., West Conshohocken, PA.

Albrecht, B.A. and Benson, C.H. (2001). Effect of desiccation on compacted natural clays, J. Geotech. and Geoenviron. Engrg, ASCE, 1: 67-75.

Al Wahab, R.M. and El-Kedrah, M.A. (1995). Using Fibers to Reduce Tension Cracks and Shrink/Swell in Compacted Clay. Geoenviron. 2000, Geotechnical Special Pub. No. 46, ASCE, New York: 791-805.

Cai Y., Shi, B., Charles, W.W. Ng. and Tang, C. (2006). Effect of polypropylene fibre and lime admixture on engineering properties of clayey soil. Engrg. Geol. 87: 230-240.

Daniel, D.E. (1987). Earthen liners for land disposal facilities. Proc. Geotechnical Practice for Waste Disposal, R.D. Woods, Ed., ASCE, Reston, Va.: 21-39.

Daniel, D.E., and Benson, C.H. (1990). Water content-density criteria for compacted soil liners. J. Geotech. Engrg, ASCE, 116(12): 1811–1830.

Daniel, D.E. and Wu, Y.K. (1993). Compacted clay liners and covers for arid sites. J. Geotech. Engrg, ASCE, 119(2): 223–237.

Dexter, A. R. and Kroesbergen, B. (1985). Methodology for determination of the tensile strength of soil aggregates. J. Agric. Engrg. Research, 31: 139-147.

Harianto, T., Hayashi, S., Du, Y.J. and Suetsugu, D. (2007). An ええvaluation of fiber admixtures on the desiccation crack behavior of the compacted Akaboku Soil potentially used as a landfill cover barrier material. Proc. 60th Canadian Geotechnical Conference and 8th Joint CGS/IAH-CNC Groundwater Conference, 1: 1377-1382.

Harianto, T., Hayashi, S., Du, Y.J. and Suetsugu, D. (2008). Experimental investigation on strength and mechanical behavior of compacted soil-fiber mixtures. Proc. of the 4th Asian Regional Conference on Geosynthetics, Shanghai, China: 392-397.

Harianto, T., Hayashi, S., Du, Y.J., and Suetsugu, D. (2008). Effects of fiber additives on the desiccation crack behavior of the compacted Akaboku Soil as a material for landfill cover barrier. Water, Air, and Soil Pollution. Springer Science, DOI 10.1007/s11270-008-9703-2, 194(1-4): 141-149.

Harianto, T., Du, Y.J., Hayashi, S., Suetsugu, D., and Nanri, Y. (2008). Geotechnical properties of soil-fiber mixture as a landfill cover barrier material. Geotech. Engrg., J. of the Southeast Asian Geotech. Society, 39(3): 137-143.

Maher, M.H. and Ho, Y.C. (1994). Mechanical properties of kaolinite fiber soil composite. J. Geotech. Engrg, 120(8): 1381-1393.

Miller, C.J. and Rifai, S. (2004). Fiber reinforcement for waste containment soil liners. J. Environ. Engrg, ASCE, 8:891-895.

Qian, X., Koerner, R.M., and Gray, D.H. (2002). Geotechnical Aspects of Landfill Design and Construction. Prentice Hall Inc., New Jersey.

Tang, C., Shi, B., Gao, W., Chen, F. and Cai, Y. (2007). Strength and mechanical behaviour of short polypropylene fiber reinforced and cement stabilized clayey soil. Geotextiles and Geomembranes, 25: 194-202.

USEPA (1989). Technical Guidance Document, Final Cap on Hazardous Waste Landfills and Surface Impoundment, EPA/530-SW-89-047, Washington D.C.

Witt, K.J. and Zeh, R.M. (2005). Cracks Due to Desiccation in Cover Lining Systems Phenomena and Design Strategy, Intl. Workshop LIRIGM, Grenoble University, France.

Ziegler, S., Leshchinsky, D., Ling, H.I. and Perry, E.D. (1998). Effect of short polymeric fibers on crack development in clays. Soils Found., 38(1): 247-253.