Strength evaluation of solid waste material included various fibrous materials

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\section*{ABSTRACT}

Clarification of shearing property of solid waste material has been required to understand the failure mechanism and to evaluate the static stability of waste ground. Past research showed that the shearing responses of waste material with fibrous materials caused a significant increase in strength and a reduced post-peak strength loss. A modeling approach is proposed in this paper for evaluating the contribution of fibrous materials to the shear strength of waste material. The reinforcement effect of fibrous materials that depends primarily on the angle between shear plane and fibrous materials orientation is defined from tensile strength of waste material. Simulations show how the effectiveness of reinforcement is captured and provide good agreement with experimental data.

\textbf{Keywords:} strength evaluation model, reinforcement effect, fibrous materials, solid waste material

\section*{1. INTRODUCTION}

Slope instabilities have occurred in several landfills and illegal dumping sites (Miyamoto et al., 2014a). These situations have caused significant economic consequence and in some cases resulted in loss of human lives. Establishment of mechanical evaluation system of waste ground has been required recently. Advanced mechanical system is also possible to produce the long-term solutions of waste problem such as improvement of landfill design and high-degree applications of landfills.

Most research regarding with mechanical behavior of waste material has presented experimental results based on soil mechanics (for example, Tawhata et al., 2007, Koelsch, 2009). Direct shear tests and triaxial compression tests have demonstrated that shear strength is increased and post-peak strength loss is reduced when fibrous materials are included in waste material. More recently Miyamoto (2014b) investigated the relationship between in-situ shearing properties and composition ratios of waste material quantitatively. It was found that the shear strength properties depend on the content rate of fibrous materials.

This paper presents a new modeling approach for predicting the shear strength of waste material focused on reinforcement effect of fibrous materials. The model to describe the shear strength increase is based on principle of superposition and it considered that the reinforcement effect calculated by the tensile strength of waste material depends on the angle between shear plane and fibrous materials orientation. The model is calibrated and simulated using experimental results.

\section*{2 MODELING FRAMEWORK}

The principle of superposition is used here for the development of a model for waste material. The shear strength of waste material reinforced with fibrous material is calculated by the unreinforced shear strength and the tensile strength. Figure. 1. shows model concept and reinforcement mechanism. The element of waste material is drawn simplify by fibrous materials and other materials (it defined waste-matrix). It has been found that the most common procedure for molding waste ground, throwing and tamping, leads to preferred sub-horizontal orientation of fibrous materials. Since the orientations of all fibrous materials are defined depositing horizontally and any angle $\theta$ represents the angle of shear plane with fibrous materials orientation.

The unreinforced shear strength of waste matrix $\tau_{mf}$ depends only on friction between each materials and it represented as following:

$$\tau_{mf} = \sigma \tan \phi_m$$  \hfill (1)

where subscript $m$ denotes the waste matrix component, and $\sigma$ and $\phi_m$ are respectively the normal stress and the friction angle of waste matrix. The tensile strength of waste material $\tau_f$ is demonstrated by pullout and/or breakage of fibrous materials. Pullout is the typical mechanism governing the failure of reinforced samples below the critical normal stress. For higher normal stress, the plastic limit and/or breakage of the fibrous materials may attain failure of waste material (Fig. 1.). Tensile strength defined in this research is considered to take place when mobilized shear resistance at the
fiber-matrix resistance at the interface has reached its maximum allowable value $\tau_T$:

$$\tau_T = c_T + \sigma \tan \varphi_T$$  \hspace{1cm} (2)

where $c_T$ is the adhesive component and $\varphi_T$ is frictional component of the interface shear strength between waste matrix and fibrous materials. In this research, $c_T$ and $\varphi_T$ are respectively defined tensile cohesion and tensile friction angle.

For the shear plane direction component of tensile strength $\tau_m$, the shear strength increase. The normal stress is also increased by equivalent stress $\tau_m \sin \theta$ acting in the normal direction of shear plane. The shear strength of waste material reinforced with fibrous materials $\tau_r$ is given by the following relationship:

$$\tau_r = \tau_m + \tau_m \sin \theta \tan \varphi_m + \tau_r \cos \theta$$  \hspace{1cm} (3)

However, the actual tensile stress and/or strength of fibrous materials embedded in waste matrix possess passive mechanism depending on the tensile strain development and also it depends on the angle $\theta$. Accordingly, it is necessary to quantify the relationship between tensile strains and angle $\theta$ for appending the angle $\theta$ dependence of tensile strength to equation (3).

To maintain simplicity in the formulations presented here, it is assumed that the minimum principal strain ($\varepsilon_1$) direction corresponds to minimum strain ($\varepsilon_1$) direction (coaxially) and the shear plane occurs when generating maximum stress ratio $\varepsilon_m / \sigma$ in waste matrix. From this approach, the angles of both $\varepsilon_1$ and $\varepsilon_2$ directions from normal direction $\eta$ can be calculated to $45^\circ - \phi_m / 2$ by using strain Mohr’s circle (Fig. 1.).

**Fig. 1.** The model concept and reinforcement mechanism

**Fig. 2.** Angle $\theta$ dependence of reinforcement effect

Tensile strain forming angle $\theta$ from normal direction $\varepsilon_1(\theta)$ is obtained by the following expression:

$$\varepsilon_\theta(\theta) = 2\sin^2(\theta + \eta) - (1 - \sin \nu)$$  \hspace{1cm} (4)

where $\nu$ is dilatancy angle of waste matrix. It is found from Fig. 1. that tensile strain when estimating tensile strength in the model represents $\varepsilon_\theta(\theta = 90^\circ)$. The strain ratio relationship between tensile strain corresponding angle $\theta(\varepsilon_\theta(\theta))$ and $\varepsilon_\theta(\theta = 90^\circ)$ is expressed by:

$$f(\theta) = \frac{\varepsilon_\theta(\theta)}{\varepsilon(\theta = 90^\circ)} = \frac{2\sin^2(\theta + \eta) - (1 - \sin \nu)}{(2\cos^2 \eta - (1 - \sin \nu))}$$  \hspace{1cm} (5)

The angle $\theta$ dependence of tensile strength is expressed by multiplying tensile strength $\tau_T$ and the strain ratio $f(\theta)$. Accordingly, the shear strength of waste material considered reinforcement effect of fibrous material is rewritten as following relationship:
\[
\tau_f = \tau_{mf} + \tau_T \times f(\theta) \times (\sin \theta \tan \varphi_m + \cos \theta) \quad (6)
\]

The substantial reinforcement effect is expressed by second term in equation (6) and its angle \( \theta \) dependence is indicated in Figure. 2. It is found from Fig. 2. that the reinforcement effect is not demonstrated under less than the angle \( \theta = \eta = 45^\circ - \phi_m / 2 \). On the other hand, the maximum reinforcement effect is demonstrated when the angle \( \theta = 45^\circ + \phi_m / 2 \).

3 MODEL CALIBRATION

The present modeling approach requires the separate calibration of the parameters governing the each unreinforced shear strength and tensile strength. The input parameter for the unreinforced shear strength is calibrated by medium-size direct shear test, while the parameters for the tensile strength influenced by fibrous materials are calibrated by large-size tensile test.

3.1 Material

The collected waste material from illegal dumping site (site B) in Japan has been used in this investigation. Its basic properties can be found in Miyamoto (2014a, b). From the composition ratios of waste material, this waste contained fibrous materials of 16.5 %, gravel and geo-materials finer 5 mm of 74.0 % in weight.

3.2 Unreinforced shear strength of waste matrix

The definition of unreinforced shear strength of waste matrix is friction strength excluding the influence of fibrous materials actually. However, it is difficult to prepare the waste specimen without fibrous materials completely. Accordingly, the direct shear test has been used to measure the unreinforced shear strength in this study because the angle \( \theta \) is easy to controlled less than \( \theta = 45^\circ - \phi_m / 2 \) (it assumed approximately \( \theta = 0^\circ \)).

The shear properties of waste material under various conditions have been investigated in this study by developed medium-size direct shear test apparatus (Miyamoto., 2014b). Figure. 3. shows the variation of secant friction angle with normal stress as the example of typical unreinforced shear strength property of waste matrix. As can be observed, the secant friction angle decreases with increasing of normal stress. Overall, the friction parameter of waste matrix \( \phi_m \) is better to be evaluated by secant friction angle \( \phi_m \).

3.3 Tensile strength influenced by fibrous materials

The tensile strength parameters have been calibrated by large-size tensile test apparatus as shown in Figure. 4, which has been developed by referring to Koelsch (2009). The tensile box consists of two tensile frames and the size of one tensile frame is 50 x 50 cm in plan of view and 50 cm high. The test procedure of tensile test is similar to conventional direct shear test. The specimen is placed into the tensile box and normal stress is applied on the sample. When the consolidation of the sample has finished or until period of twenty minutes, one frame is moved by displacement rate of 1 mm / min. All the specimens were fabricated as dry density of 0.80 g / cm³ with water content of 20 %. Figure. 5. shows tensile strength and normal stress relationship. The tensile parameters estimated form this figure indicate the tensile cohesion \( c_T \) of 10.3 kN / m² and the tensile friction angle \( \phi_T \) of 18.2 degree.

4 MODEL SIMULATION

This proposed model has been used to simulate the shear strength of waste material reinforced with fibrous materials. Here it is important that the anisotropy of reinforcement effect, which depends on the direction angle between shear plane and fibrous materials \( \theta \), can be evaluated by this model. Accordingly, the direct
Shear test varying the angle \( \theta \) were performed to compare with the model simulation. The specimens, which fibrous materials have the certain direction angles from shear plane \( \theta = 0, 30, 45, 60, 90 \, ^{\circ} \), were fabricated using mold and angle guide as shown in Figure. 6. All the specimens were fabricated as dry density of 0.80 g / cm\(^3\) with water content of 20 % and shearing under normal stress of 25 kN / m\(^2\). Figure. 7 shows the relationship between shear stress and shear displacement depending on the angle \( \theta \). The remarkable difference of reinforcement effect depending on the angle \( \theta \) is observed and the distinct peak strength does not appear with shearing deformation. In this study, the shear strength is defined as the mobilized shear stress at a shear displacement of 40 mm, which is the maximum displacement measured accurately by this apparatus.

A summary of the input parameters for the model simulation is presented in Table. 1. Figure. 8 compares model simulation with experimental result. The model simulation predicts very well satisfactorily the shear strength of waste material with fibrous materials which has anisotropic reinforcement depending on the direction angle between shear plane and fibrous materials orientation.

### 5 CONCLUSIONS

A simple modeling approach for the shear strength of waste material reinforced with fibrous materials has been presented, based on the principle of superposition. Its application has been consisted by the unreinforced shear strength and the tensile strength. The calibration and simulation results of this model are also presented from experimental work. Accordingly, it became clear that the unreinforced shear strength is better to be evaluated by secant friction angle and the tensile strength can be evaluated by tensile cohesion and tensile friction angle. The anisotropy of reinforcement effect was also evaluated focusing on the angle between shear plane and fibrous materials orientation. Model simulation captured the anisotropic reinforcement effect and provided a good agreement with experimental data.

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### REFERENCES

1) Koelsch, F. (2009): Shear Strength of waste, Proc. the Third International Workshop “Hydro-Physico-Mechanics of Landfills “, Braunschweig, Germany.
2) Miyamoto, S., Yasufuku, N., Ishikura, R., Omine, K., Kawai, S. and Yamawaki, A. (2014a): Shearing response and shear strength of solid waste material conducted by developed direct shear test apparatus, Proc. 10\(^{th}\) ICG, Berlin, Germany.
3) Miyamoto, S., Yasufuku, N., Ishikura, R., Omine, K., Kawai, S. and Yamawaki, A. (2014b): In-situ shearing response and shear strength of various solid waste ground focused on fibrous materials composition, Proc. Geomechanics from micro to macro, Cambridge, UK, 1357-1362.
4) Towhata, I. and Uno, M. (2007): Laboratory Tests on Creep and Shear Behavior of Municipal Solid Waste and Mitigation of Its Long-Term Subsidence, Proc. GeoCongress 2008, New Orleans, 152-159.

| Shear parameters | Tensile parameters |
|------------------|-------------------|
| Secant angle, \( \phi_s \) | Dilatancy angle, \( \nu \) | Tensile cohesion, \( c_T \) | Tensile friction angle, \( \phi_t \) |
| 44.0 \(^{\circ}\) | 0 \(^{\circ}\) | 10.3 kN / m\(^2\) | 18.2 \(^{\circ}\) |

**Table 1. Input parameters for model simulation**

| Dry density, \( \rho_{d0} \) | Water content, \( w \) | Normal stress, \( \sigma \) |
|-----------------------------|-----------------|------------------|
| 0.80 g / cm\(^3\) | 20.0 % | 25.0 kN / m\(^2\) |

**Fig. 6. Configuration of mold and angle guide**

**Fig. 7. Configuration of mold and angle guide**

**Fig. 8. Configuration of mold and angle guide**

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**Figures:**

1. Fig. 6: Configuration of mold and angle guide
2. Fig. 7: Configuration of mold and angle guide
3. Fig. 8: Configuration of mold and angle guide