# Simplified Prediction of Changes in Shear Strength in Geotechnical Use of Drinking Water Sludge

## Prédiction simplifiée de changements dans la force du ciseau dans usage Geotechnical de boue de l'eau potable

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ABSTRACT: Drinking water sludge is the aggregation of clay and organic compounds which is formed in flocculation and sedimentation process. This study focused on the decomposition of the bonding by flocculating agent and organic matter, and proposed a simplified method for the prediction of changes in shear strength caused by DWS decompositions. The changes in shear strength of DWS were investigated by triaxial compression tests. The specimens were produced using the DWS which was mainly decomposed by $H_2O_2$ solutions. As a result, volumetric strain became large in the large axial strain range, and the maximum deviator stress decreased concomitantly with the decrease in ignition loss. After the organic matter was decomposed until 1.38%, the internal friction angle decreased from approximately 38.8° to 37.6°. The changes of shear strength were related to the substantial period in geotechnical works such as road infrastructures. The decompositions of the mechanical bridging and organic matter were described based on diffusion-controlled Al leaching and aerobic biodegradation, respectively.

RÉSUMÉ : La boue de l'eau potable est l'agrégation d'argile et composés organiques qui sont formées dans le flocculation et processus de la sédimentation. Cette étude s'est concentrée sur la décomposition de la liaison par agent du flocculating et matière organique et a proposé une méthode simplifiée pour la prédiction de changements dans la force du ciseau causée par les décompositions DWS. Les changements dans la force du ciseau de DWS ont été enquêtés par les épreuves de la compression du triaxial. Les spécimens ont été produits utiliser le DWS qui était principalement décomposé par les solutions $H_2O_2$. En conséquence, la tension volumétrique est devenue grande dans la grande gamme de la tension axiale, et le stress du déviateur maximal a diminué de façon concomitante avec la baisse dans la perte de l'ignition. Après que la matière organique ait été décomposée jusqu'à 1.38%, l'angle de la friction interne a diminué d'approximativement 38.8° à 37. 6°. Les changements de force du ciseau ont été mis en rapport avec période substantielle dans le geotechnical travaille tel qu'infrastructures de route. Les décompositions de la mécanique qui lie et la matière organique a été décrite basé sur Al diffusion-contrôlé qui lessive et biodégradation aérobique, respectivement.

KEYWORDS: waste, sludge, reuse, organic matter, decomposition, aluminum, leaching, shear strength

## 1 INTRODUCTION

Drinking water sludge (DWS) which is discharged during water purification is presently classified as industrial waste in Japan. A microphotograph of DWS is represented in Fig. 1. DWS is the aggregation of clay and organic compounds which is formed in flocculation and sedimentation process. Reuse and disposal of DWS are an important viewpoint in the sound material-cycle society.

The geotechnical use of DWS such as a road infrastructure material is greatly anticipated. So far, mechanical and leaching characteristics of DWS have been investigated (Roque and Carvalho, 2006; Watanabe et al., 2009). Specifically, it is presumed that Al leaching results from the Al-type flocculating agent. Watanabe et al. (2011) showed that the organic matter decomposition decreased in shear strength of DWS. To reuse DWS safely, the evaluation of the durability is strongly required. Therefore, this study focused on the decomposition of the bonding by flocculating agent and organic matter, and proposed a simplified method for the prediction of changes in shear strength caused by DWS decompositions in geotechnical works.

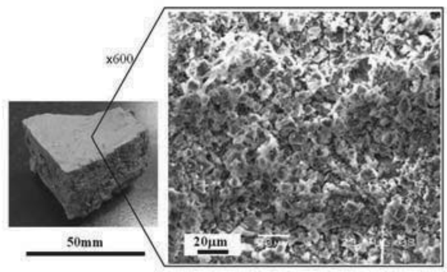



Figure 1. Microphotograph of DWS.

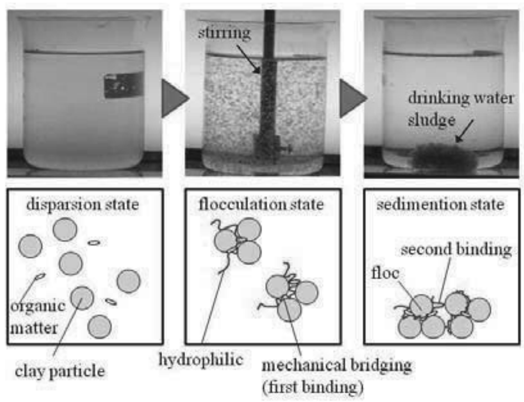



Figure 2. Schematic DWS formation process.

## 2 DECOMPOSITION MECHANISM

The DWS formation during water purification process is based on two phases in Fig. 2. Less than $10^{-6}$ m diameter particles including organic matter were flocculated by chemicals as first binding, and floc settled and consolidated (Montgomery, 1985). Bonding force is generated by the mechanical bridging of flocculating agent: polyaluminum

Table 1. Fundamental properties of DWS.

| DWS | Particle density of soil ($Mg/m^3$) | Liquid limit (%) | Plastic limit (%) | Ignition loss(%) | Fulvic acid (%) | Humic acid (%) |
|---|---|---|---|---|---|---|
| A | 2.58 | 224 | 145 | 17.6 | 0.039 | 3.14 |
| B | 2.61 | 178 | 104 | 18.8 | 0.032 | 2.39 |
| C | 2.52 | 269 | 151 | 26.6 | 0.034 | 9.27 |
| D | 2.45 | 113 | 91 | 27.3 | 0.040 | 4.31 |
| E | 2.54 | | | 17.1 | 0.016 | 1.20 |
| F | 2.65 | | | 22.1 | 0.049 | 3.90 |
| G | 2.45 | | | 19.1 | 0.036 | 5.14 |

chloride is frequently used in Japan. Some hydrophilic parts of flocculating agent remain and bind clods as second binding, then more than $10^{-5}$ m diameter clods presumably form DWS's porous structure as shown in Fig. 1.

In this study, DWS was sampled in Ibaraki, Japan. Approximate organic matter content of DWS was determined by ignition loss tests. The ignition loss and fundamental properties were listed in Table 1. Ignition loss of DWS was 17.6%−27.3%. The amount of humic and fulvic acids were determind by alkaline and acid isolation (Ohkubo et al., 1998). Specifically, humic acid content was dominant for DWS. It is indicated that organic matter exists in as a solid part and a bonding as well as the mechanical bridging. A main constituent of polyaluminum chloride is $Al_2O_3$. Previous study has been already confirmed Al leaching by column leaching tests in Fig. 3 (Watanabe et al., 2009). Organic matter decomposition at 30 degrees has been confirmed in Fig. 4 (Watanabe et al., 2011), which means the loss of DWS particles and binders. Consequently, engineering properties of DWS after the decomposition mentioned above are interest on a discussion of DWS durability.

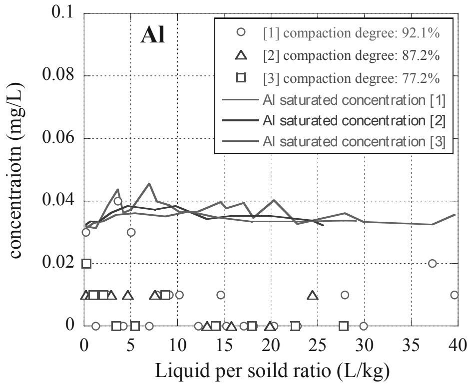



Figure 3. Al concentration in column leaching tests (Watanabe et al., 2009).

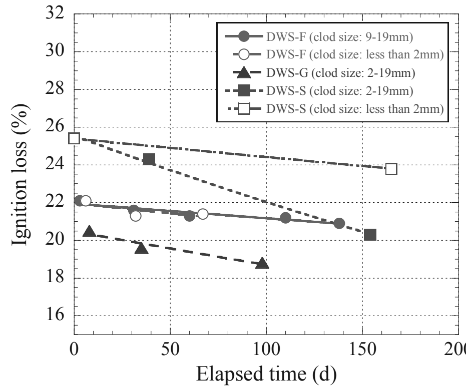



Figure 4. Changes of ignition loss of DWS at 30 deg. (Watanabe et al., 2011).

## 3 RELATION BETWEEN SHEAR STRENGTH AND DECOMPOSITION

Shear characteristics of DWS after decomposition were investigated to elucidate the necessity of the mechanical bridging and organic matter on DWS's structure. The DWS which was mainly decomposed by $H_2O_2$ solution was used in triaxial compression tests.

### *3.1 Experimental procedure*

Triaxial compression tests were executed using the DWS for which the mechanical bridging and organic matter had been decomposed by the $H_2O_2$ solution. The apparatus for the triaxial compression tests is portrayed in Fig. 5. The specimen had 100-mm height and 50-mm diameter. Specimens were produced by dynamic compaction using DWS-A. The dry density in CASES 1–4 was 0.815–0.825 $Mg/m^3$ which corresponds to compaction degree 76%. First, the specimen was isotropically confined by 10 kPa. Then the $H_2O_2$ solution (6%, 9%, 15%) was percolated through the specimen by 10 kPa of water pressure. Specimens in CASES 2, 3 and 4 were decomposed by the $H_2O_2$ solution. During $H_2O_2$ percolation, $CO_2$ was generated by oxidation. The $CO_2$ continuously flow into the sealed desiccator, and the $CO_2$ concentration was measured using a wireless $CO_2$ sensor. The completion of oxidation was confirmed as the $CO_2$ concentration converged, which prevented partial saturation of the specimen during shearing. The decrease in organic matter by $H_2O_2$ has been investigated in Table 2. The discharged water was collected, and Al concentration was measured. The distilled water was percolated after $H_2O_2$ percolation, and more than 0.95 of the B-value was confirmed for specimen saturation. The isotropic consolidation pressure was 50 kPa or 100 kPa. The triaxial tests were executed in the drainage condition with 0.1%/min of the strain rate.

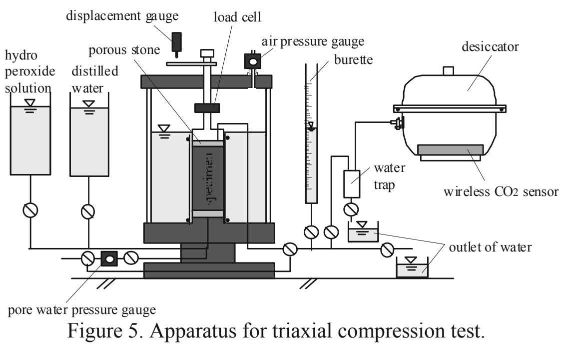
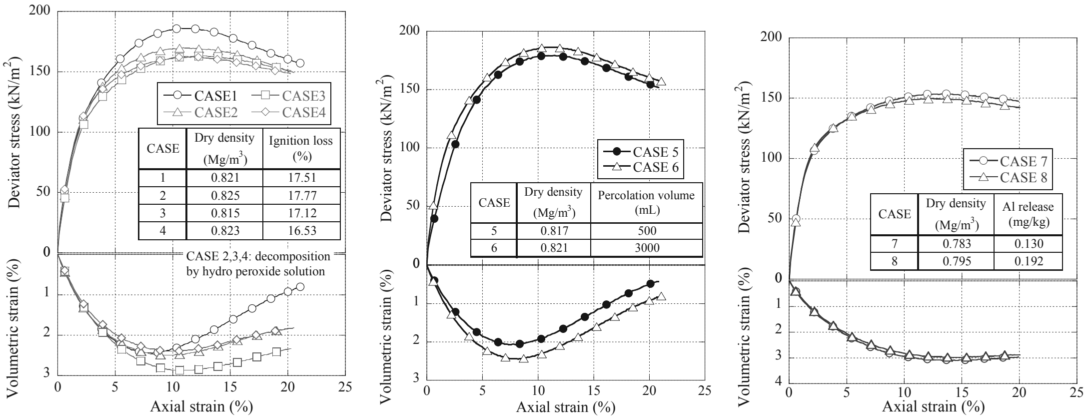



Figure 5. Apparatus for triaxial compression test.

Table 2. Decomposition rate of organic matter by 6% hydrogen peroxide solution for 24 h.

| DWS | Decomposition rate (%) | | |
|---|---|---|---|
| | Fulvic acid | Humic acid | Humin and soil particles |
| B | 77.1 | 44.9 | 3.1 |
| C | 86.5 | 43.2 | 8.1 |
| D | 88.0 | 46.6 | 10.3 |
| E | 73.4 | 42.5 | 6.6 |




(a) $H_2O_2$ percolation (b) distilled water percolation (c) pH 4.0 water submergence

Figure 6. Relation between deviator stress and axial strain in triaxial compression tests using decomposed DWS.

As mentioned above, Al leaches during $H_2O_2$ percolation. The deformation of the mechanical bridging by Al leaching causes at the same time as organic matter decomposition. To distinguish the influence of Al leaching on the mechanical deformation from organic matter decomposition, shear characteristics of the DWS for which the mechanical bridging had been decomposed by leaching using distilled water adjust pH 4.0 using $HNO_3$ which was almost same pH as $H_2O_2$ solutions were also investigated in CASE 5 to 8. In acidic condition, humic acid almost remains in DWS, although fulvic acid is decomposed. In CASE 7 and 8, samples previously submerged in $HNO_3$ repeatedly, and the specimens were produced by dynamic compaction using the decomposed sample.

### *3.2 Experimental results*

The respective relations between the deviator stress and the volumetric strain to axial strain at 50 kPa of confined pressure was presented in Fig. 6. Volumetric swelling was slight in the large axial strain range, and the maximum deviator stress decreased concomitantly with the decrease in ignition loss. For the cases of distilled water percolation, the influence of percolation volume was not obtained. The larger dry density typically showed higher shear strength. For the cases of pH 4.0 water submergence, maximum deviator stress slightly decreased and cumulative Al release increased with the increment of submergence. The influence of Al release on shear strength was relatively smaller than those of organic matter decomposition.

The internal friction angle and the cohesion of DWS after organic matter decomposition were, respectively, 38.6° and 0 $kN/m^2$. The mechanical bridging and the organic matter decomposition do not influence DWS cohesion. Assuming that the cohesion is 0 $kN/m^2$, the relation between the internal friction angle and the decomposition rate of organic matter was presented in Fig. 7. After the organic matter was decomposed until 1.38%, the internal friction angle decreased from approximately 38.8° to 37.6°. For the cases of pH 4.0 water submergence, the internal friction angle decreased from 37.2° to 36.7° although the dry density was smaller than any others. Consequently, results show that the decomposition of organic matter remarkably affects to the DWS shear strength. Chemical bonding between particles by the cementation of organic compounds is possible (Mitchell and Soga, 2005). Presumably, the strength of DWS clods decreased because the bonding was lost through organic matter decomposition.

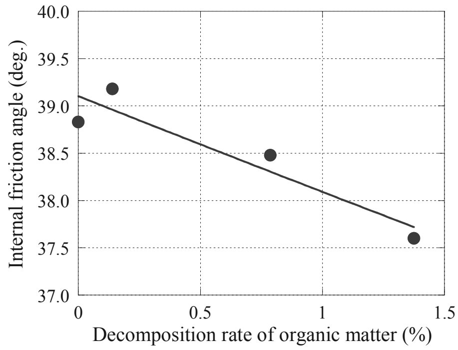



Figure 7. Relation between internal friction angle and decomposition rate of organic matter.

## 4 PREDICTION OF SHEAR STRENGTH TRANSITION

Al release and organic matter decomposition cause the decrease in shear strength of DWS. To evaluate the durability of DWS as a geo-material, this study related the change of its shear strength the decomposition to the substantial period in geotechnical works such as road infrastructures.

### *4.1 Shear strength transition addressing decomposition of mechanical bridging*

Decomposition of the mechanical bridging is described as Al leaching behavior. When DWS is used as a subgrade material under groundwater level, Al diffusively leaches. Therefore, the Al leaching behavior is described as a diffusion equation based on the Fick's law.

$$\frac{\partial C}{\partial t} = D_e \frac{\partial^2 C}{\partial x^2} \qquad (1)$$

In that equation, $D_e$ is the coefficient of diffusion [$m^2/s$], $C$ is the concentration [mg/L], and $x$ signifies the distance from particle surface [m]. An initial condition and boundary conditions are shown as follows.

$$t = 0,\ x \le 0; C = C_0$$
$$t > 0,\ x = 0; C = C_1, t > 0,\ x = -\infty; C = C_0$$

where $C_0$ represents the internal concentration of material [mg/L], and $C_1$ is the constant concentration [mg/L]. Assuming $C_0$ is sufficiently higher than $C_1$, the cumulative release $M$ is derived.

$$M = 2C_0\sqrt{\frac{D_e}{\pi}}\left(t_2 - t_1\right) \tag{2}$$

$D_e$ of Al is $4.77\times10^{-15}$ $m^2/s$ which was obtained by the serial batch leaching test (Watanabe et al., 2010). As $t_1$ is 0, the Eq. 2 transforms to Eq. 3, and it relates the cumulative Al release $M_{exp}$ obtained in the triaxial tests to the elapsed time $T$.

$$T = \frac{M_{\exp}^2 \cdot \pi}{4C_0^2 \cdot D_e} \tag{3}$$

Therefore, the transition of the internal friction angle caused by decomposing the mechanical bridging is calculated as shown in Table 3. Approximate 1.3% decrease in the internal friction angle supposedly causes during 38 years.

### 4.2 *Shear strength transition addressing decomposition of organic matter*

The organic matter decomposition of DWS as a subgrade material is able to be interpreted as following, assuming aerobic and unsaturated condition. Jenny (1941) described the decrease in soil organic matter as Eq. 4.

$$\frac{dX}{dt} = rX \tag{4}$$

where $X$ is the mass of organic matter and $r$ is the rate of decomposition. A solution of Eq. 4 is given by Eq. 5.

$$X = X_0 \cdot e^{-rt} \tag{5}$$

Assuming aerobic biodegradation, discharged $CO_2$ is originated from the carbon loss of decomposed organic matter approximately. From the results of constant temperature storage in aerobic condition of DWS (Watanabe et al., 2011), $r$ is determined by fitting Eq. 5 into the experimental data as shown in Fig. 8. The daily $CO_2$ discharge during organic matter decomposition corresponds to the decomposition mass of organic matter, so the time integral of Eq. 5 approximately represents the total mass of decomposed organic matter $Q_{dec}$.

$$Q_{dec} = \frac{X_0}{r}\left(e^{-et_1} - e^{-rt_2}\right)\times\frac{12}{44} \tag{6}$$

Calculation results for the transition of the internal friction angle caused by decomposing the organic matter are listed in Table 4. Approximate 3.1% decrease in the internal friction angle by organic matter decomposition causes during 22 days in aerobic condition. Assumption of aerobic condition is not suitable for practice, so this study confirmed the organic matter decomposition in site. In the experimental construction that DWS was used as a backfill material of water pipe construction, the DWS layer was taken a position of -0.4 to -0.9 m depth under asphalt surface. The compaction degree was approximate 64–76%. The monitoring term was 19 months. As shown in Table 5, ignition loss slightly decreased at the end of the experiment. It is presumed that organic matter decomposition slowly progressed in contrast to the constant temperature storage because of anaerobic condition and lower temperature. The proposed method with aerobic condition excessively estimates the degradation in contrast of underground conditions.

## 5 CONCLUSIONS

DWS is the aggregation of clay and organic compounds. Focusing on the chemical bonding by flocculating agent and organic matter, a simplified method for the prediction of changes in shear strength of DWS in geotechnical works was proposed. The decomposition of the mechanical bridging and the organic matter was described based on diffusion-controlled Al leaching and aerobic biodegradation, respectively. The methodology proposed in this paper is significant to encourage safe geotechnical utilizations through estimations of the usable term for not only DWS but also available waste or by-products.

Table 3. Shear strength transition addressing decomposing the mechanical bridging.

| Cumulative Al release (mg/kg) | Calculated elapsed time (y) | Internal friction angle (deg.) |
|---|---|---|
| 0 | 0 | 37.2 |
| 0.130 | 17.4 | 37.6 |
| 0.192 | 38.0 | 36.7 |

Table 4. Shear strength transition addressing decomposing the organic matter.

| Decomposition rate of organic matter (%) | Calculated elapsed time (d) | Internal friction angle (deg.) |
|---|---|---|
| 0 | 0 | 38.8 |
| 0.14 | 2 | 39.2 |
| 0.79 | 12 | 38.5 |
| 1.38 | 22 | 37.6 |

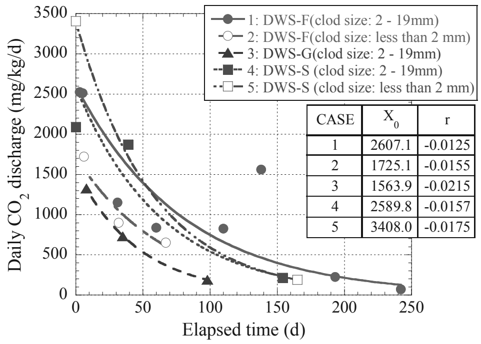


Figure 8. Results of constant temperature storage in aerobic condition of DWS (Watanabe et al., 2011).

Table 5. In-situ monitoring results of ignition loss of DWS

| | Compaction degree (%) | CBR (%) | Ignition loss (%) | |
|---|---|---|---|---|
| | | | before construction | 19 months later |
| Air-dried DWS | 75.9 | 38.1 | 16.9 | 16.6 |
| Filter-pressed DWS | 64.3 | 55.3 | 24.7 | 24.0 |

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