### Title

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DEGRADATION OF DRINKING WATER SLUDGE FOR LONG-TERM WASTE MANAGEMENT

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ABSTRACT: Drinking water sludge is industrial waste which is discharged during water purification, and it is presently anticipated to reuse drinking water sludge as geotechnical material. However, degradation has not been investigated. To keep strength, stability, and safety on long-term waste management, it is important to apply degradation characteristics to designing and maintenance. As an aspect of degradation on drinking water sludge, variation of consolidation properties induced interaction with water is discussed in this paper. The slight influence of degradation as to consolidation properties is shown. Furthermore, the elapsed time for progression of degradation is calculated by using leaching flux.

Keywords: waste management, geoenvironmental engineering, drinking water sludge, degradation, consolidation, aluminum leaching

INTRODUCTION

Management of industrial waste is important for sound material-cycle society, which is represented as 3Rs (reduce, recycle, reuse) in Japan, against the background of confined final disposal site. In public water service, drinking water sludge is discharged during water purification, and classified as industrial waste in Japan (Fig. 1). Presently, it is anticipated for utilizing drinking water sludge as geotechnical material such as road or embankment in terms of mechanical strength (Roque and Carvalho, 2006, Bae et al., 2007). Environmental impact has been also assessed because drinking water sludge generally contained flocculating agent, poly-aluminum chloride, in Japan (Watanabe et al., 2007).

However, degradation of drinking water sludge is not investigated. Sludge is usually degraded by decomposition, which influenced consolidation properties (O’Kelly, 2005). Especially, drinking water sludge is formed by chemical combination of flocculating agent, so interaction with water accelerates to leach flocculating agent and decompose (Watanabe et al., 2008). On the long-term waste management, application of degradation characteristics to design and maintenance is significantly important.

Initial objective in this study is to establish evaluation method of degradation on drinking water sludge by combining mechanical and chemical properties changes. This study has so far investigated the degradation

Figure 1. Drinking water sludge: (a) air-drying mat in water purification plant, (b) air-dried sludge, (c) filter-pressed sludge (2 mm in thickness)
mechanism on drinking water sludge by focusing on chemical composition that drinking water sludge contains flocculating agent; poly-aluminum chloride, and discussed that dissolution of the flocculating agent is the dominant matter on degradation (Watanabe et al., 2008). In this paper, this study focuses compression and consolidation properties on drinking water sludge in order to clarify the influence of degradation. Firstly, aluminum leaching from drinking water sludge was accelerated, and constant strain rate consolidation test was conducted. Second, elapsed time in degradation process was calculated by using the result of leaching test.

### Experimental Procedure

Constant strain rate consolidation test accepted by Japanese industrial standard (JIS A 1227:2000) was conducted on air-dried sludge, filter-pressed sludge and degraded sludge. Air-dried sludge was sampled in Ibaraki prefecture, and filter-pressed sludge was sampled in Hiroshima prefecture in Japan (Fig. 1).

#### Table 1. Physico-chemical properties of drinking water sludge

<table>
<thead>
<tr>
<th>Sample</th>
<th>Air-dried sludge</th>
<th>Filter-pressed sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desiccation type</td>
<td>Air-dry</td>
<td>Filter-press system</td>
</tr>
<tr>
<td>Sampling place</td>
<td>Hitachi, Ibaraki, Japan</td>
<td>Hiroshima, Hiroshima, Japan</td>
</tr>
<tr>
<td>Soil particle density (Mg/m³)</td>
<td>2.610</td>
<td>2.396</td>
</tr>
<tr>
<td>Ignition loss (%)</td>
<td>18.8</td>
<td>25.5</td>
</tr>
<tr>
<td>Flocculating agent</td>
<td>Poly-aluminum chloride</td>
<td>Liquid aluminum sulfate</td>
</tr>
</tbody>
</table>

In Japan, filter-press system is recently familiarized in order to increase efficiency of desiccation. Filter-press system can desiccate sludge up to near plastic limit, and the desiccation mechanism is based on consolidation (Watanabe et al., 2007). The shape of filter-pressed sludge is differs from those of air-dried sludge, and it is required to investigate the difference of consolidation properties. Physico-chemical properties of the sludge were listed in Table 1. Incidentally, air-dried sludge contained poly-aluminum chloride, and filter-pressed sludge contained liquid aluminum sulfate as representative flocculating agent. Degraded sludge was prepared using air-dried sludge by submergence in distilled water before consolidation test. Firstly, specimen was submerged for 24h by adjusting liquid per solid to 10 to 1(Fig. 2). Second, the specimen was air-dried for 24h to dewater up to initial water content. This degradation operation was repeated from one to three times on each specimen.

The test apparatus for constant strain rate consolidation test is described in Fig. 3. The test apparatus can operate one-dimensional constant strain, and measure pore water pressure and vertical stress and strain. Specimen size was 60 mm in diameter and 20 mm in height. Specimen was made by dynamic compaction under the same compaction energy, simulating road construction. All test started with 0.01 mm/min in constant strain and one-side drainage condition. Pore water pressure which increases at un-drainage side is used on calculating coefficient of consolidation and hydraulic conductivity.
EXPERIMENTAL RESULT AND DISCUSSION

Compression curve of air-dried sludge, filter-pressed sludge, and degraded sludge, are respectively shown in Fig. 4. Figure 5 describes the relationship between compression index and dry density. Initial void ratio related to dry density of specimen, and dry density was dependant on initial water content. The larger dry density showed the higher yield consolidation pressure. Especially, compression index of filter-pressed sludge decreased by desiccation to natural water content. In general, drinking water sludge has high water content right after discharging, so it is necessary to desiccate to lower water content. Influence of degradation on compression behavior was not obtained. Consequently, influence of desiccation method and degradation is very small in the case of more than 0.85 Mg/m$^3$ in dry density, which was corresponding to 80 % of compaction degrees on drinking water sludge sampled in Hitachi (Bae et al., 2007). Figure 6 shows the pore water pressure in comparison between air-dried sludge ($\rho_d=1.050$ Mg/m$^3$) and degraded sludge ($\rho_d=1.016$ Mg/m$^3$). Pore water pressure of air-dried sludge increased along compressive strain, while pore water pressure of degraded sludge decreased approximately 0.4 kN/m$^2$ and increased after 5 % of compressive strain. In constant strain rate consolidation test, decrease of pore water pressure is caused by crushed clod and high hydraulic conductivity. It is supposed that drinking water sludge becomes weaker and compressive by degradation.

Coefficient of consolidation ($c_v$) was calculated from pore water pressure using eq. (1) (Wissa et al, 1971).

$$c_v = \frac{H^2}{2u_{av}} \Delta \sigma \times 1440$$  \hspace{1cm} (1)

where $\Delta t$ is infinitesimal time and, $H_{ave}$ is averaged height of specimen during $\Delta t$, and $\Delta \sigma$ is increase of consolidation pressure during $\Delta t$, and $u_i$ is pore water pressure changed during $\Delta t$. 

![](image1.png) Figure 2. Degradation method

![](image2.png) Figure 3. Test apparatus for constant strain rate consolidation test
Void ratio
Compression pressure (kN/m²)

Void ratio
Consolidation pressure (kN/m²)

Void ratio
Consolidation pressure (kN/m²)

(a) Air-dried sludge
(b) Filter-pressed sludge
(c) Degraded sludge

Figure 4. Compression curve

Dry density of specimen (Mg/m³)

Figure 5. Relationship between compression index and dry density

Figure 6. Pore water pressure in comparison between air-dried sludge and degraded sludge
Coefficient of consolidation of drinking water sludge is shown in Fig. 7. Calculated $c_v$ sharply decreased in over consolidation. After that, $c_v$ increased and peak point came out in air-dried sludge, meanwhile, $c_v$ of degraded sludge was negative because of disappearance of pore water pressure (Fig. 6). $c_v$ decreased after yield consolidation pressure. Consequently, consolidation properties of drinking water sludge is defined both compression and consolidation process, and degradation tends to expand the behavior of compression.

Hydraulic conductivity $k$ was calculated from $c_v$ using eq. (2).

$$k = \frac{\gamma_w H_{\text{ave}} \Delta H}{2 u_{\text{ave}} \Delta t} \times \frac{1}{60 \times 100}$$

(2)

where $\gamma_w$ is unit weight of water, and $\Delta t$ is increase of height during $\Delta t$. Eq. (2) is based on consolidation theory given by eq. (3).

$$c_v = \frac{k}{\gamma_w m_v}$$

(3)

where $m_v$ is coefficient of volume compressibility.

Calculated hydraulic conductivity is shown in Fig. 7. Calculated results using negative pore water pressure were also negative; not realistic, so those results were not shown in Fig. 8. Thus, this study obtained hydraulic conductivity from the first compressive strain; air-dried sludge was $2.5 \times 10^{-5}$ (cm/s) and degraded sludge was $6.0 \times 10^{-5}$ (cm/s). After degradation, hydraulic conductivity slightly decreased, but the influence of degradation on hydraulic conductivity was not appeared on compression curve (Fig. 4). Incidentally, hydraulic conductivity of air-dried sludge was almost same as the result of hydraulic conductivity test (JIS A 1218); $2.83 \times 10^{-5}$ (cm/s) (Bae et al., 2007).

**DEGRADATION AND ELAPSED TIME**

On utilization of drinking water sludge as well as long-term waste management, it is important to predict degradation and time, so this study represented elapsed time on consolidation properties changes by using flocculating agent leaching flux.
LEACHING FLUX

Firstly, this study analyzed cumulative aluminum concentration; Al₂O₃, in accelerated degradation process, because degradation is accelerated by flocculating agent leaching (Watanabe et al., 2008). Second, this study executed serial batch test, and calculated leaching flux using eq. (4).

\[ J = c \times q = \frac{L/S \times a + b}{n \times 1m^3} \]

where \( J \) represents leaching flux and \( n \) represents porosity, and \( a \) and \( b \) are obtained from slope and intercept in the results of serial batch test (Fig. 9).

![Figure 9. Serial batch test results and calculation theory](image)

Cumulative aluminum concentration and calculated elapsed time were listed in Table 2. 0.05 mg/L of Al₂O₃ concentration corresponded to 6.9 year passage. Consequently, it is expected that drinking water sludge has no influence of degradation for 6.9 years in the case of road embankment as to consolidation properties. However, it is remarkable to consider dry density in specification because leaching flux is dependent on permeability which depends on dry density.

![Figure 10. Concept of aluminum leaching flux of drinking water sludge](image)
Table 2. Calculation results of degradation and elapsed time corresponding to cumulative aluminum concentration

<table>
<thead>
<tr>
<th>Degradation process</th>
<th>24h submergence ×1</th>
<th>24h submergence ×2</th>
<th>24h submergence ×3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry density of degraded sludge specimen (Mg/m³)</td>
<td>1.019</td>
<td>1.015</td>
<td>1.016</td>
</tr>
<tr>
<td>Compression index</td>
<td>0.524</td>
<td>0.513</td>
<td>0.538</td>
</tr>
<tr>
<td>Hydraulic conductivity (cm/s)</td>
<td>Not obtained</td>
<td>Not obtained</td>
<td>6.0 × 10⁻⁵</td>
</tr>
<tr>
<td>Cumulative leached Al₂O₃ concentration (mg/L)</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Elapsed time (year)</td>
<td>5.3</td>
<td>6.9</td>
<td>6.9</td>
</tr>
</tbody>
</table>

CONCLUSION

Remarkable conclusions were obtained as followings.

(1) It is important to desiccate drinking water sludge to lower water content in order to improve compressibility, and then, there was almost no difference on compression index of air-dried sludge, filter-pressed sludge, and degraded sludge at more than 0.85 Mg/m³ in dry density.

(2) The influence of degradation caused by aluminum leaching on compressibility was hardly shown, while hydraulic conductivity slightly increased after degradation.

(3) Elapsed time was calculated from results of serial batch test by using leaching flux. 0.05 mg/L of cumulative aluminum concentration corresponded to 6.9 years passage. Consequently, it is presumed that drinking water sludge has no influence of degradation by aluminum leaching for 6.9 years in terms of compression and consolidation properties.

(4) This paper indicated that it was useful for long-term waste management to focus on dry density and hydraulic conductivity which were relating to degradation of drinking water sludge.

REFERENCES


