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Technical Paper

# Early-stage anaerobic zone formation by organic eluate from wood in soil

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**Abstract**

When separated soil (SS) generated from the Great East Japan Earthquake, which contains woodchips and others (WC), is utilized as ground material, microorganisms decompose the organic carbon in WC, and oxygen is consumed in the process. This reaction results in forming an anaerobic zone and generating methane gas. To effectively utilize SS as ground material, it is necessary to prevent anaerobic zone formation to ensure safety. This study clarified the relationship between WC content and the concentration of leached organic carbon (TOC) and the relationship between TOC concentration in the eluate and the oxygen consumption rate were clarified. We obtained the relationship between WC content and the extent of anaerobic zone formation from the results,. The anaerobic zone is formed below the oxygen penetration depth ($L_{O2}$). $L_{O2}$ rapidly decreases as the WC weight ratio increases from 0 to 1 w%, and $L_{O2}$ is almost constant, i.e., around 1 to 2 m above 1 w% WC weight ratio. An increase in WC weight ratio does not significantly decrease $L_{O2}$ determined by the aerobic decomposition of the solution. From the above, contamination with WC should be limited to 1 w% or less to prevent the formation of an anaerobic zone. If SS has WC above 1 w%, it is required to put a ventilating layer such as crushed stone every few meters or the other countermeasures when SS is utilized as ground material.


*Keywords:* Woodchip; Separated soil; Organic carbon; Oxygen consumption rate; Anaerobic zone; Methane gas

## 1. Background

The tsunami generated approximately 31 million tons of disaster waste and deposits after the Great East Japan Earthquake in 2011 (Japan Ministry of the Environment (ME), 2017). After collecting valuable materials such as metals, concrete blocks, and wood, residual soil-like fine particles were obtained from the disaster waste and deposits. The residual soil-like fine particles are called separated soil (SS) in Japan (Japan ME, 2017). It is considered that organic carbon in the form of woodchips and others (WC) derived from homes destroyed by the earthquake and tsunami is mixed in SS. In the same way, soils containing wood particles are generated in torrential rain, resulting in landslides and the subsequent destruction of wooden houses or trees. Japan ME (2012) intends to use SS as ground material for backfilling or banking. However, The Japanese Geotechnical Society (2014) has pointed out that SS contains organic matter such as WC, which could be an

*AbbreviationsSS, separated soil; WC, woodchips and others; ME, Ministry of the Environment; TOC, (total) organic carbon; IL, ignition loss; CDW, construction and demolition waste; SIW, shredded incombustible municipal solid waste.*

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environmental hazard depending on the WC content and the environment surrounding SS. The hazards include ground subsidence and polluted water and gas (mainly methane gas) after WC decomposition. Methane gas is a greenhouse gas, and high concentrations may cause an explosion. Therefore, we should control methane gas generation due to SS utilization.

Microorganisms may decompose organic carbon in WC and consume oxygen when SS containing WC is utilized as ground material (Lenz et al., 2015; Kaltschmitt et al., 2016; Hofmann et al., 2018; Mpholo et al., 2018; Pecenka et al., 2018; Kuptz et al., 2020; Hu et al., 2021). This reaction may result in forming an anaerobic zone and generating methane gas (He et al., 2012; Whittaker et al., 2016). Methane gas is generated from forest soil (Yavitt et al., 1995; Jacinthe, 2015), particularly in wet areas (Sorrell and Boon, 1994; Savage et al., 2014; Wong et al., 2018; Cabezas et al., 2018). Similarly, the combination of WC and wet soil would lead to methane gas generation. As decomposing wood in an anaerobic environment also generated methane gas at a solid waste landfill site (Rees, 1980; Barlaz, 2006; Milke et al., 2010; Ximenes et al., 2015; O'Dwyer et al., 2018), SS containing WC in an aerobic zone should generate methane gas.

Excavated soil generated in foundation work is utilized effectively as ground material in Japan. The Japanese Geotechnical Society (2014) stated that SS could be used as an equivalent of excavated soil on condition that the SS contains a small amount of organic matter such as WC. However, they did not provide an acceptable standard of organic matter content. Japan ME (2017) introduced some cases of quality evaluation on SS utilization as ground material in disaster-stricken areas. In some instances, staff at separation facilities checked SS by visual inspection to prevent contamination by particles of gypsum board, asbestos, and organic matter such as WC. SS that underwent proper separation and foreign matter removal was utilized as ground material. In addition, Japan ME (2017) conducted a questionnaire survey that administrators of SS separation facilities participated. One of the questionnaire respondents stated, "We could not ship some SS because WC was detected by visual inspection. It would be good if there were a quantitative evaluation method." An acceptable standard of WC content is needed to accelerate SS utilization.

To effectively utilize SS as ground material, it is necessary to prevent anaerobic zone formation to ensure safety. When SS is used as ground material, the elution of organic carbon from mixed WC (Iseki et al., 1984; Abusallout and Hua, 2017), the aerobic decomposition of the eluted organic carbon by microorganisms (Lenz et al., 2015; Kaltschmitt et al., 2016; Xu et al., 2021), and the consumption of oxygen by microorganisms may result in the formation of an anaerobic zone (He et al., 2012; Whittaker et al., 2016). In theory, a high WC content induces the leaching of organic carbon (Bantle et al., 2014), oxygen consumption, and the subsequent expansion of the anaerobic zone. In the case of deposited SS, an anaerobic zone is formed at a distance from the surface as air enters from the surface (Tanaka et al., 1986). If the relationship between WC content and the extent of anaerobic zone formation were known, we would be able to propose the maximum allowable content or thickness of WC for SS utilization. Knowledge of the maximum permissible WC content or thickness would accelerate the effective utilization of SS and the development of technology for WC removal from SS whose WC content exceeds the maximum permissible content. Tanaka et al. (1986) introduced a method for calculating the oxygen penetration depth into a solid waste layer using the oxygen consumption rate and other parameters. This method can also calculate the extent of anaerobic zone formation. This study focused on gas generation, particularly methane gas, among known environmental hazards. This study dealt with not long-term WC decomposition but the formation of an anaerobic zone by organic carbon leached from WC at an early stage.

The objectives of this study were as follows:

1. to clarify the relationship between WC content and the concentration of leached organic carbon (TOC); and
2. to determine the relationship between the TOC concentration in the eluate and the oxygen consumption rate.

We obtained the relationship between WC content and the extent of anaerobic zone formation from the results.

## 2. Materials and methods

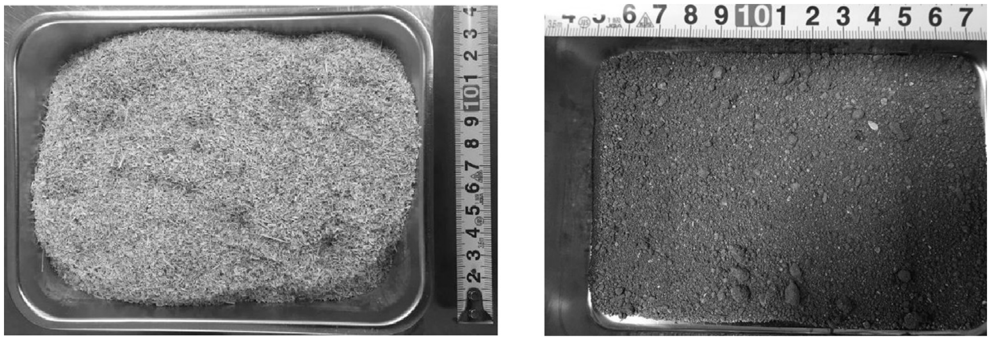
### 2.1. Materials

Larch was chosen as WC. It was ground in an electric blender (Waring Laboratory Blender LB-15, OSAKA CHEMICAL Co., Ltd.) and sieved to obtain four different particle sizes. Particle sizes of 10 to 5 mm, 5 to 1 mm, 1 to 0.5 mm, and 0.5 to 0.1 mm were called X, dL, M (Fig. 1(a)), and S, respectively. The percentages of timber by wood species produced in Japan in 2017 were 90.0% for needle-leaved trees (Japanese cedar 57.3, white cedar 12.9, larch 10.7, and red pine 3.0%) and 10.1% for broad-leaved trees (Japan MAFF, 2017d). Therefore, larch ranks third in production amount and is a major species in Japan.

In addition, SS generated by the Great East Japan Earthquake and whose large wood particles have been removed was used as a sample (called "initial soil" (Fig. 1(b)), hereinafter).

### 2.2. Physicochemical characteristics

Ignition loss of WC $IL_{\mathrm{wood}}$ (800 °C, 3 h) was measured. Moisture content $\omega$ (105 °C, 24 h), ignition loss $IL_{\mathrm{ini}}$, particle density $\rho_{\mathrm{p}}$ (pycnometer method, JIS A 1202), and bulk density $\rho_{\mathrm{d}}$ (filled densely into a sampling bucket with a tamper rod and dried at 105 °C for 24 h) of initial soil were measured.



(a) (b)

Fig. 1. Materials. (a): Larch M, (b): Initial soil.

### 2.3. Elution test

Larch and water were mixed at various solid–liquid ratios (weight-WC/volume-water (g/mL), $R_{SL}$, hereinafter) and particle sizes. The mixtures were shaken, the eluates were sampled at predetermined times, and TOCs were measured. Details are as follows. A predetermined amount of WC (1.4, 2.8, 5.6, 14, or 28 g) and 70 mL of pure water (ion-exchanged) were transferred into plastic bottles (Fig. 2), and the $R_{SL}$ values were 0.02, 0.04, 0.08, 0.20, and 0.40, respectively. For example, the condition of $R_{SL}$: 0.02 and particle size: L is called 002L. TOCs were not measured for 020 M, 020S, 040 M, and 040S because fine particles of WC absorbed most of the water, making eluate sampling impossible. The plastic bottles were shaken at 100 rpm. At predetermined times (0, 1, 2, 5, 10, 24, 48, 120, 240, and 720 h), 2 mL eluates were sampled by inserting a plastic syringe into the bottles and passed through a 0.45 μm pore size filter (DISMIC®-25CS Cellulose Acetate 0.45 μm Hydrophilic) to obtain the filtrates (WC extract, hereinafter). TOC in WC extract was measured by a Shimadzu TOC-V.

### 2.4. Oxygen consumption rate

WC extracts were inoculated with soil containing decomposing wood, and oxygen consumption rates by aerobic decomposition of organic carbon in the WC extracts were measured. The details are as follows. WC extracts were diluted to 0, 36, 73, 180, 370, 660, 1200, 3000, and 5800 mg-C/L of TOC. A 100 mL portion of each of the diluted solutions was transferred into a DURAN® bottle having a volume of 200 mL. Then, 5 mL of nutrient solution (500 mL water and BOD Nutrient Buffer Pillows for 6 L sample APHA Formulation, HACH), 0.5 mL of inoculum solution (extract from a mixture of water, decomposing branches on the ground, soil under the branches, and bark compost), 1 g of silica sand, and a stirring bar were added into the bottle. The bottle was capped with pressure sensor OxiTop-C (WTW) and carbon dioxide absorbent (NaOH pellet), and placed in an incubator (Fig. 3). The stirrer was set at 10 rpm, and the temperature was set at 20 or 35 °C. Aerobic bacteria consume oxygen, decompose organic carbon in the diluted solutions, and generate carbon dioxide. As the absorbent removes carbon dioxide,

Fig. 2. Elution test.

Fig. 3. Measurement of oxygen consumption rate.

the gas pressure in the bottle will decrease with oxygen consumption. The gas pressures at the predetermined times were measured (n = 3). The pressure decrease rate was converted into the oxygen consumption rate.

## 3. Results

### 3.1. Physicochemical characteristics

Ignition loss of WC $IL_{wood}$ was 99.7% (mean, n = 3). Moisture content $\omega$, ignition loss $IL_{ini}$, particle density $\rho_p$, and bulk density $\rho_d$ were 22.2 w%, 3.87%, 2.65 t/m$^3$, and 1.18 t/m$^3$, respectively (mean, n = 3).

### 3.2. Elution test

Examples of the relationship between shaking time and TOC in WC extract are shown in Fig. 4 ($R_{SL}$ 0.02) and Fig. 5 (particle size X). The smaller the particle size, the higher the maximum TOC concentration at the same solid–liquid ratio. The larger the solid–liquid ratio, the higher the maximum TOC concentration at the same particle size. Regarding $R_{SL}$ 0.40 in Fig. 5, the increase of TOC concentration was rapid from 0 to 50 h and mild around 120 h (5 d), and plateaued after 240 h (10 d). No change in concentration was observed after 240 h in all conditions.

The relationship between solid–liquid ratio $R_{SL}$ and TOC in WC extract at 720 h (day 30) is shown in Fig. 6. The regression line is determined with the TOC values of X and L due to missing M and S. $R_{SL}$ and TOC have a linear relationship. However, the smaller the particle size, the higher the maximum TOC concentration, as shown in Fig. 4, i.e., the TOC values of M and S were found above the regression line. As WC extract of small particles could not be sampled, and the data were omitted, the high TOC of M and S shown in Fig. 6 did not influence the determination of the regression line. However, obtaining omitted data should be a future issue.

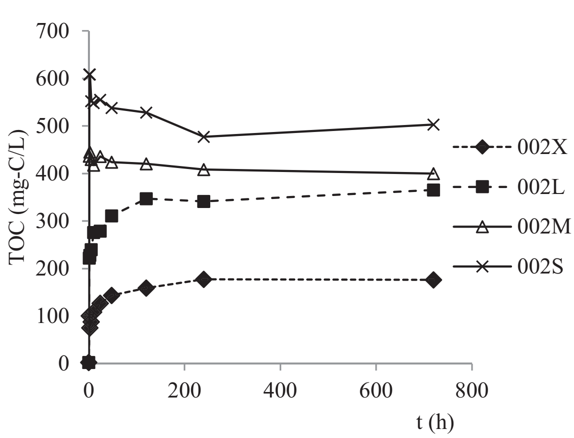



Fig. 4. Relationship between shaking time and TOC in WC extract ($R_{SL}$ 0.02).

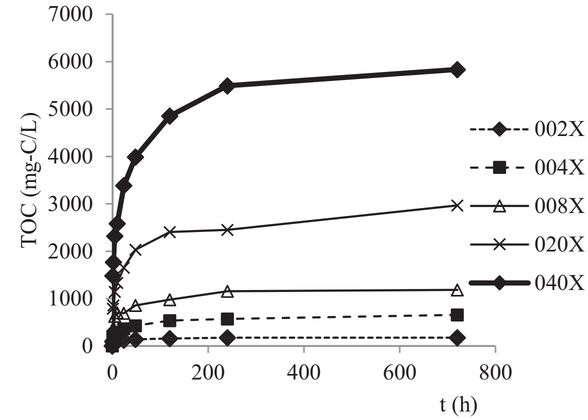



Fig. 5. Relationship between shaking time and TOC in WC extract (particle size X).

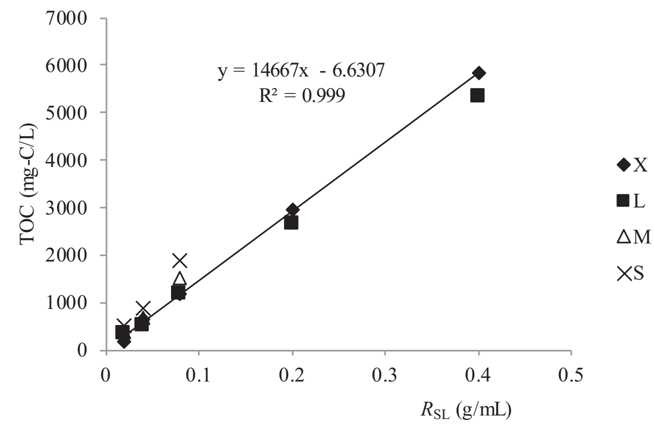



Fig. 6. Relationship between solid–liquid ratio $R_{SL}$ and TOC in WC extract (on day 30). The regression line is determined with the TOC values of X and L.

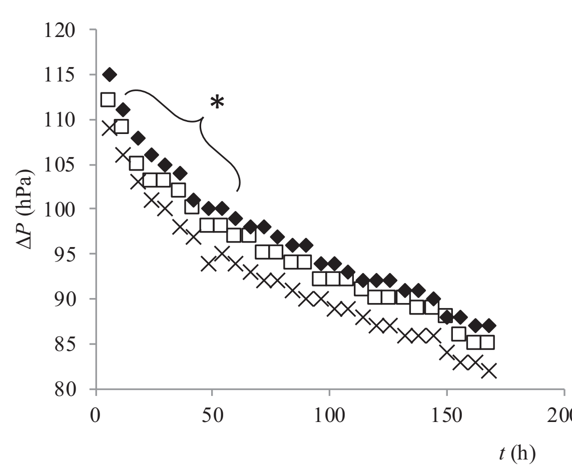



Fig. 7. Relationship between elapsed time and gas pressure of diluted solution (370 mg-C/L of TOC, 35 $^{O}$C, n = 3). The pressure decrease rate was obtained using data with *.

### 3.3. Oxygen consumption rate

As mentioned above, gas pressures in the bottles were measured to determine the oxygen consumption rate. For example, the relationship between elapsed time and gas pressure of the diluted solution containing 370 mg-C/L of TOC at 35 $^{O}$C is shown in Fig. 7. The pressure decreased with time. To predict the most dangerous side, i.e., the maximum anaerobic zone, the pressure decrease rate was obtained using data that showed a large inclination at an early stage (* in Fig. 7). The pressure decrease rate was converted into the oxygen consumption rate $R_{O2}$ [mmol-$O_2$/(L·h)] using Eq. (1) and Eq. (2).

Ideal gas law:

$$\Delta PV = \Delta nRT$$

$$\Delta n = \Delta PV/(RT)$$

$$\Delta n/t = (\Delta P/t)(V/(RT)) \quad (1)$$

$$R_{O2} = (\Delta n/t)(1000/V_{solution}) \quad (2)$$

where $\Delta P$ is pressure decrease [Pa]; $V$ is air volume in a DURAN® bottle [m$^3$]; $n$ is amount of oxygen [mol-$O_2$]; $R$ is gas constant (=8.314) [m$^3$·Pa /(mol·K)]; $T$ is temperature [K]; $t$ is elapsed time [h]; and $V_{solution}$ is solution volume [L].

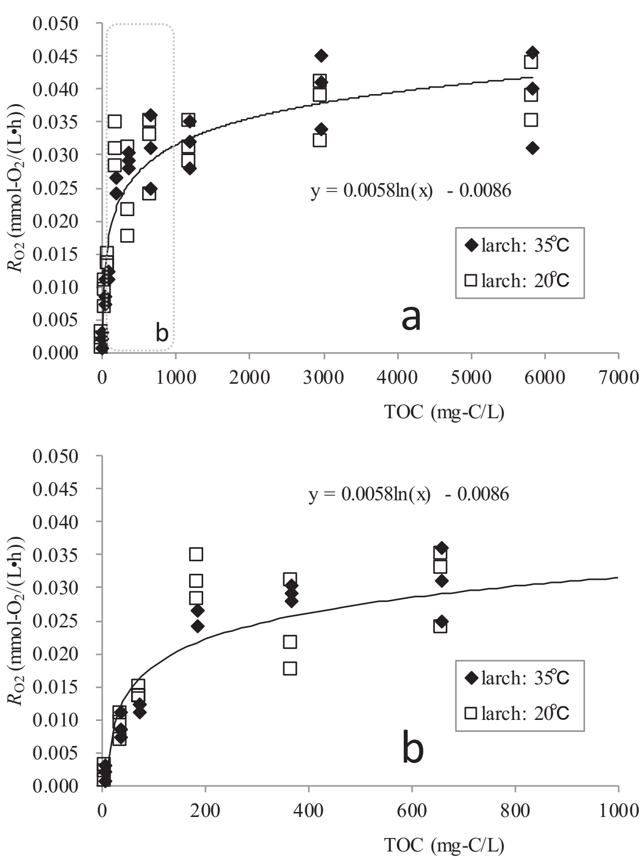



Fig. 8. Relationship between TOC (a: 0–7000 mg-C/L, b: 0–1000 mg-C/L) and oxygen consumption rate $R_{O2}$.

The relationship between TOC and oxygen consumption rate $R_{O2}$ is shown in Fig. 8. The oxygen consumption rate increased as TOC increased; however, the oxygen consumption rate reached a plateau at higher TOCs. This phenomenon is a general tendency and is the same as the Michaelis-Menten equation expressing the relationship between substrate concentration and the initial velocity of an enzymatic reaction. By curve fitting, coefficients a and b in equation $y = a \log_e x + b$ ($y$: oxygen consumption rate $R_{O2}$ [mmol-$O_2$/(L·h)], $x$: TOC [mg-C/L]) were obtained (see Fig. 8). There was no significant difference in the oxygen consumption rate $R_{O2}$ at 20 °C and 35 °C. Therefore, curve fitting was performed using data from both temperatures. We were able to convert TOC into the oxygen consumption rate by using the equation.

## 4. Discussion

### 4.1. Relationship between WC content in SS and oxygen penetration depth

Here we consider the oxygen penetration depth when SS is added to the original ground as backfill. As SS contains WC, TOC in WC is eluted by permeating rainwater. When microorganisms aerobically decompose TOC in pore water, oxygen gas in the pore is consumed. When the oxygen concentration in the pores of SS is lower than that in the atmosphere, oxygen in the atmosphere diffuses into and penetrates SS based on the concentration gradient. Therefore, oxygen penetration depth can be calculated by the balance between the oxygen penetration rate and the oxygen consumption rate. The oxygen penetration rate can be determined based on the characteristics of the pores in SS (tortuosity and gas-filled porosity). The oxygen consumption rate can be measured directly. An aerobic zone is formed from the top surface of SS to the oxygen penetration depth, and an anaerobic zone is formed below the penetration depth. Fig. 9 shows a conceptual diagram of the utilization of SS as ground material. Tanaka et al. (1986) developed a calculation method for the oxygen penetration

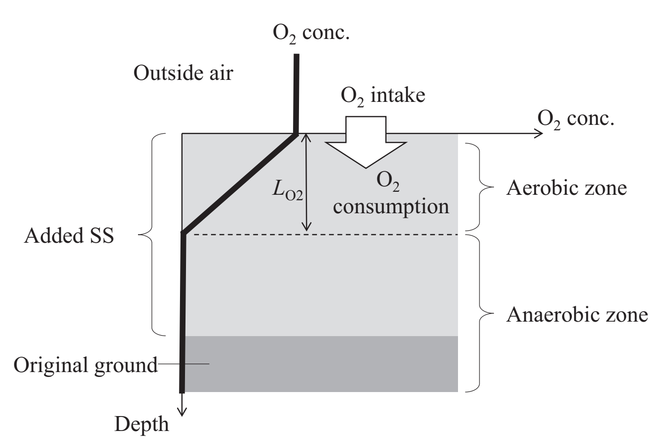



Fig. 9. Conceptual diagram of the utilization of SS as ground material.

depth into porous material with oxygen advection (occurring as a result of a temperature gradient) and diffusion (occurring as a result of a concentration gradient) flow. If we expect an advection flow, we need to install a vent pipe or its equivalent into the lower layer of SS. However, we cannot apply the vent pipe when SS is used as a backfill. Therefore, we consider only the diffusion flow of oxygen from the top surface of SS in this study. A derivation process was also illustrated in a previous survey (Asakura et al., 2009). An outline of the derivation process of oxygen penetration depth $L_{O2}$ [m] is shown in the following.

$$L_{O2} = (0.42\ /\beta)^{0.5} \tag{3}$$

$$\beta \equiv (\xi/\varepsilon)(RT/P)(1/D_{k1} + 0.21/D_{12} + 0.79/D_{13})(R_{02}\prime) \tag{4}$$

where $\xi$ is tortuosity [–]; $\varepsilon$ is gas-filled porosity [–]; $R$ is gas constant (=8.314) [$m^3$·Pa /(mol·K)]; $T$ is temperature [K], $P$ is total pressure [Pa]; $D_{ij}$ is bulk diffusion coefficient for gas combination i, j [$m^2$/s] ($D_{12} = 1.87 \times 10^{-5}$, $D_{13} = 1.81 \times 10^{-5}$ $m^2$/s at 0 °C, 1 atm; subscripts "1, 2, and 3″ are $O_2$, $CO_2$, and $N_2$ + Ar, respectively); $D_{ki}$ is the Knudsen diffusion coefficient [$m^2$/s] (=0.532 $r\,(RT/M_i)^{0.5}$) of component i ($M_i$ and $r$ are the molecular weight of component i [kg/mol] and the equivalent pore radius [m], respectively); and $R'_{O2}$ is the oxygen consumption rate [mol/($m^3$·s)]. The obtained $L_{O2}$ value that satisfies Eq. (3) is the oxygen penetration depth [m], and $L_{O2}$ $R'_{O2}$ is the oxygen penetration flux [mol/($m^2$·s)].

When $T$, $P$, $D_{12}$, and $D_{13}$ are constant, $\xi/\varepsilon$, $r$, and $R'_{O2}$ influence $L_{O2}$. A large $r$, a small $\xi/\varepsilon$, or a small $R'_{O2}$ causes a large $L_{O2}$, i.e., a large aerobic zone. At first, some literature values were extrapolated to the equivalent pore radius $r$. As $T$ has a negligible influence on $L_{O2}$ at temperatures between 293 K (20 °C) and 303 K (30 °C), $T$ was set at 298 K (25 °C). $P$ was set at the standard atmosphere (101,325 Pa). We obtained the Knudsen diffusion coefficient of oxygen, i.e., $D_{k1,}$ using the above $r$ and $T$. Then, some literature values were extrapolated to $\xi/\varepsilon$. Finally, $\beta$ was calculated from Eq. (4) using $R'_{O2}$, and subsequently $L_{O2}$, from Eq. (3).

Considering SS, which is composed of initial soil (having no wood) contaminated with WC, the calculation method for $R'_{O2}$ at various WC weight ratios in SS $C_{wood}$ [w%] is described as follows. It is difficult to measure $C_{wood}$, so the conversion method to $IL$ is also described.

At first, we assume an initial soil sample having an apparent volume of 1 $m^3$. The bulk density $\rho_d$ is also the initial soil's dry weight [t]. The $\omega$ [w%] obtained in this study is used as the moisture content of the initial soil dewatered by gravity.

Volume water content $\omega_v$ [$m^3$-water/$m^3$] is calculated using dry weight and moisture content. Water density is assumed to be 1 t/$m^3$.

$$\omega_v = \rho_d\omega/(100 - \omega) \tag{5}$$

$\omega_v$ is also the water volume of the initial soil [$m^3$-water].

Next, we assume SS, composed of initial soil contaminated with WC. WC is assumed to fill the pores of the initial soil. The range of the WC weight ratio is assumed to be from 0.05 to 10 w%. WC weight $W_{wood}$ [t/$m^3$] and ignition loss of SS $IL_{ss}$ [w%] are calculated with the dry weight of the initial soil. Although the bulk density of SS containing WC should be used for Eq. (6), the WC weight is assumed to be a negligible value.

$$W_{wood} = \rho_d C_{wood}/(100 - C_{wood}) \tag{6}$$

$$IL_{ss} = (\rho_d IL_{ini} + W_{wood} IL_{wood})/(\rho_d + W_{wood}) \tag{7}$$

The ratio of WC weight to volume water content, i.e., solid–liquid ratio $R_{SL}$ [g/mL or t/$m^3$], is calculated.

$$R_{SL} = W_{wood}/\omega_v \tag{8}$$

TOC [mg-C/L] is calculated using Eq. (8) and the equation in Fig. 6.

$$TOC = 14667R_{SL} - 6.6 \tag{9}$$

Oxygen consumption rate $R_{O2}$ [mmol-$O_2$/(L•h)] is calculated with TOC and the equation in Fig. 8. The oxygen consumption rate by a liquid is converted into oxygen consumption rate $R'_{O2}$ by 1 $m^3$ of SS [mol/($m^3$•s)].

$$R_{O2} = 0.0058\ ln\ (TOC) - 0.0086 \tag{10}$$

$$R_{O2}\prime = R_{O2}\omega_v/60/60$$

We can obtain $R'_{O2}$ from the above, and $L_{O2}$ is subsequently calculated with Eq. (3) and Eq. (4). some literature values were extrapolated into $r$ and $\xi/\varepsilon$ (Table 1). There are few reports of both values together. As construction and demolition waste (CDW) is sandy-like material that remained after collecting valuable materials, it would have similar characteristics to SS assumed in this study. When $r$ is large, the pore diameter is large, and fluid can easily pass through. Similarly, when $\xi/\varepsilon$ is small, the pore pathway is close to a straight line without bends. Although CDW, shredded incombustible municipal solid waste (SIW), and ash have relatively large equivalent pore radius $r$, there are some obstructions to fluid passage because of bends. On the other hand, although clay and silt have relatively small $r$, the passage is fairly straight. The relationship between input: WC weight ratio $C_{wood}$ [w%] and output:

Table 1
Assumed characteristics of pore in SS.

| | $r$ | $\xi/\varepsilon$ | Reference |
|---|---|---|---|
| | m | – | |
| CDW* | $3.9 \times 10^{-5}$ | 16 | Asakura et al., 2009 |
| SIW** | $2.5 \times 10^{-4}$ | 40 | Kallel et al., 2004 |
| ash*** | $1.4 \times 10^{-4}$ | 55 | Kallel et al., 2004 |
| clay | $10^{-7}$ | 6 | Tanaka et al., 1986 |
| silt | $10^{-6}$ | 4 | Tanaka et al., 1986 |

* Construction and demolition waste.
** Shredded incombustible municipal solid waste.
*** Bottom ash from an incineration facility for municipal solid waste.

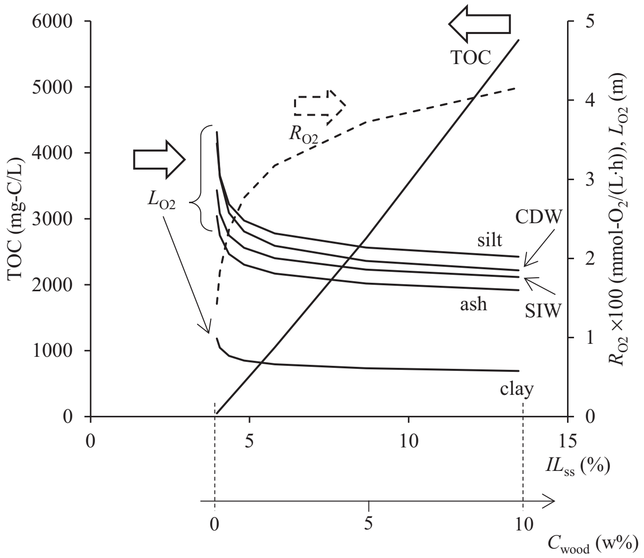



Fig. 10. Relationship between WC weight ratio $C_{wood}$ and oxygen penetration depth $L_{O2}$.

oxygen penetration depth $L_{O2}$ [m] is shown in Fig. 10. In addition, ignition loss of SS $IL_{ss}$ [%] as input and TOC and oxygen consumption rate $R_{O2}$ [mmol-$O_2$/(L•h)] as output are also shown in Fig. 10. Because the initial soil has $IL_{ini}$ despite having no WC, $IL_{ss}$ is approximately 4% at 0 w% of $C_{wood}$. $L_{O2}$ rapidly decreases as $C_{wood}$ increases from 0 to 1 w%, and $L_{O2}$ is almost constant above 1 w% $C_{wood}$. Regarding CDW, SIW, ash, and silt, $L_{O2}$ is around 2 m above 1 w% $C_{wood}$; on the other hand, it is below 1 m for clay. In this way, such characteristics as $r$ and $\xi/\varepsilon$ assumed for the initial soil influence the oxygen penetration depth. According to the calculation method in this study, TOC will increase with increasing WC weight ratio, and subsequently, $R'_{O2}$ will increase. This increase in $R'_{O2}$ decreases $L_{O2}$ in Eq. (3). However, according to Fig. 8, $R_{O2}$ reaches a plateau at higher TOC; therefore, the reduction of $L_{O2}$ is moderate. The increase in the WC weight ratio does not significantly decrease the oxygen penetration depth determined by the aerobic decomposition of the solution. It should be noted that the minimum $L_{O2}$ is calculated in this study because the maximum concentration of TOC is used.

From the above, contamination with WC should be limited to 1 w% or less to prevent the formation of an anaerobic zone. If SS has WC above 1 w%, a ventilating layer such as crushed stone should be installed every few meters when SS is utilized as ground material. Assuming 2 m of $L_{O2}$, 2 m above and below the ventilating layer, i.e., 4 m thickness, can be aerated. In that case, advection will occur, and the aerobic zone will be increased. When the weight of 1 $m^3$ SS is assumed to be 1000 kg, 1 w% of WC will correspond to 10 kg, which is quite a lot.

### 4.2. Problems and further study

#### 4.2.1. Problems in this study

In this study, larch, which ranks third in production amount and is a major species in Japan, was chosen as WC. Japanese cedar and white cedar, which have higher consumption, should be used in future studies.

The moisture content of the initial soil dewatered by gravity has been used to calculate the oxygen penetration depth. However, if WC content increases, more moisture must be held. Actual moisture content in the condition of dewatering by gravity should be measured.

The actual pore characteristics, such as $r$ and $\xi/\varepsilon$, of SS should be used to calculate the oxygen penetration depth. However, it would be helpful to know how much difference the pore characteristics cause concerning the extent of anaerobic zone formation. The calculation method is shown and can be used to propose an acceptable standard of WC content by inputting the assumed $r$, $\xi/\varepsilon$, and $R'_{O2}$.

#### 4.2.2. Further study

In this study, phenomena occurring at an early stage, i.e., elution of organic carbon from mixed WC, subsequent aerobic decomposition by microorganisms, and oxygen consumption, have been discussed. This method will allow us to consider the extent of anaerobic zone formation for SS containing WC the adjacent ground having no WC and into which eluate flows.

This study targeted to estimate the area of the early-stage aerobic zone. Therefore the saturated TOC values (Fig. 5) were adopted for an indicator of ability to make the ground anaerobic. In contrast, the long-term behavior of the aerobic zone, which is out of this study, should be estimated from the potential TOC contents like the initial TOC increasing rate. The aerobic decomposition of organic carbon in the eluate and long-term phenomena should be considered in a future study. The formation of an anaerobic zone after the aerobic decomposition of WC itself should be considered. The anaerobic zone will be expanded if the oxygen consumption of the WC itself is added.

As a final consideration, methane gas generation flux from the anaerobic zone where WC is present has to be measured to judge whether the concentration of methane gas would reach levels high enough to cause an explosion or not. A large deposition thickness can easily cause the formation of an anaerobic zone. However, as aerobic soil can oxidize methane gas (Steudler et al., 1989; Whalen et al., 1992; Jacinthe, 2015; Subke et al., 2018), SS in contact with the atmosphere can oxidize part of methane gas. Furthermore, the oxidation of methane gas in the anaerobic zone has been reported (Parsaeifard et al., 2020). Therefore, the evaluation of net methane gas generation flux is complicated (Bender and Conrad, 1992; Jones and Nedwell, 1993).

## 5. Conclusion

This study clarified the relationship between WC content and the concentration of leached organic carbon (TOC) and the relationship between TOC concentration in the eluate and the oxygen consumption rate. By combining the results, we obtained the relationship between WC content and the extent of anaerobic zone formation.

The relationship between the ratio of WC weight to volume water content (solid–liquid ratio $R_{SL}$ [g/mL]) and TOC [mg-C/L] is shown by the following equation: TOC = 14667 $R_{SL}$ – 6.6. The relationship between TOC and oxygen consumption rate $R_{O2}$ [mmol-$O_2$/(L•h)] is shown by the following equation: $R_{O2}$ = 0.0058 ln (TOC) – 0.0086. Oxygen penetration depth $L_{O2}$ of SS was calculated using the oxygen consumption rate. An anaerobic zone was formed below the oxygen penetration depth.

$L_{O2}$ rapidly decreased with increasing $C_{wood}$ from 0 to 1 w%, and $L_{O2}$ was almost constant above 1 w% $C_{wood}$. Regarding CDW, SIW, ash, and silt, $L_{O2}$ was around 2 m above 1 w% $C_{wood}$ and below 1 m for clay. An increase in WC weight ratio did not significantly decrease oxygen penetration depth determined by the aerobic decomposition of solution.

From the above, contamination with WC should be limited to 1 w% or less to prevent the formation of an anaerobic zone. If SS has WC above 1 w%, a ventilating layer such as crushed stone should be installed every few meters when SS is utilized as ground material.

The aerobic decomposition of organic carbon in the eluate and long-term phenomena should be considered in a future study. The formation of an anaerobic zone after the aerobic decomposition of WC itself should be considered.

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