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Mechanical behavior of soils recovered from disaster debris-soil mixed with wood chips during wood decay for effective utilization

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ABSTRACT: The key to early recovery from huge natural disaster is how to efficiently treat and use soils recovered from disaster debris. The objective of this study is to understand the mechanical properties of the soils recovered from disaster debris-soil mixed with wood chips during wood decay for the effective use as a geomaterial. The specimens of soil mixed with wood chips were buried in the fungus cellar, which accelerated wood chip decay, and were removed after 3, 9, and 20 months, and their mechanical behavior with wood chip decay was evaluated by triaxial compression tests. The test results were reproduced by the elasto-plastic constitutive model, the SYS Cam-clay model to interpret the effect of wood decay on the mechanical behavior of the soil based on the concept of soil skeletal structure. New main findings are as follows: 1) In the case of S9C1, the soil with a shorter burial period showed an increase in q accompanied by an increase in p' (hardening accompanied with plastic expansion). On the other hand, as the burial period increased, the degree of plastic expansion decreased, and the soil softened with plastic compression. From the replicated calculations using the model, it was interpreted that the degree of structure increases, the overconsolidation ratio decreases, and the structure becomes more susceptible to deterioration as the burial period increases. 2) In the case of S6C4, the softening behavior with plastic compression was observed regardless of the burial period, and the degree of plastic compression, maximum deviator stress and residual strength were almost equal. Reproduced calculations using the model indicated that the initial structure was larger with wood chip decay, while the structure was less susceptible to degradation in shear than S9C1, and that the change in overconsolidation ratio was smaller.

KEYWORDS: Disaster waste, triaxial compression test, constitutive equation.

1 INTRODUCTION

In recent years, Japan has experienced huge natural disasters, which have caused devastating damage to local areas generated massive amounts of disaster waste. The total amount of disaster waste reached approximately 31 million tons in the Great East Japan Earthquake (Ministry of Environment, 2014). The 2024 Noto Peninsula E In addition, frequent heavy rain disasters in recent years—such as the 2018 Western Japan Heavy Rain, the Heavy Rain in July 2020, and the heavy rainfall in Wajima City, Ishikawa Prefecture—have brought attention to the challenge of managing sediment-related waste. Furthermore, it is estimated that the anticipated Nankai Trough Earthquake could produce up to 350 million tons of disaster waste—approximately 11 times the amount generated by the Great East Japan Earthquake (Ministry of Environment, 2013).

Efficient processing and disposal of the massive volume of disaster waste is critical to achieve rapid recovery and reconstruction. However, within the overall flow of disaster waste treatment, the processing of soil-waste mixtures remains a bottleneck. Meanwhile, according to the Iwate Prefecture Reconstruction Material Utilization Manual (Updated Version) (Iwate Prefecture, 2013), the separated soils obtained through advanced processing such as recovered soil types B and C, may be utilized as reconstruction materials depending on future research outcomes.

The objective of this study is to explore the effective use of recovered soil as geotechnical materials, focusing in particular on simulated recovered soils containing wood chips, and to investigate the mechanical properties considering the effects of wood chip decay.

2 MATERIAL AND TEST PROCEDURES

2.1 *Physical properties of base material and wood chips*

To simulate recovered soil types B and C, mixed soil composed of Masado and Kasaoka clay was used as the base material. The base material was prepared with two mixing ratios: Masado to Kasaoka clay at 9:1 and 6:4 (Takai et al, 2016). The former was considered a sand-dominant base material, and the latter a clay-dominant one, designated as S9C1 and S6C4, respectively. The particle densities were 2.64 g/cm³ for S9C1 and 2.66 g/cm³ for S6C4.

Figure 1 shows the grain size distribution, and Figure 2 shows the compaction curves. Regarding the mixing of wood chips into the base material, shredded wood chips of less than 4.75mm were added to S9C1 at dry weight ratios of 1.5% and to S6C4 at 1.5%.

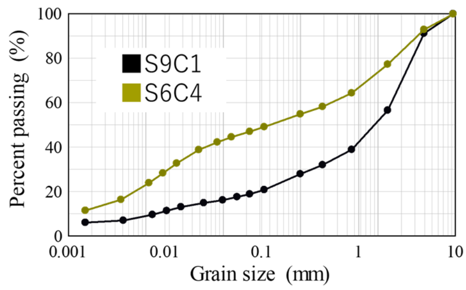

Figure 1. Grain size distribution of base material.

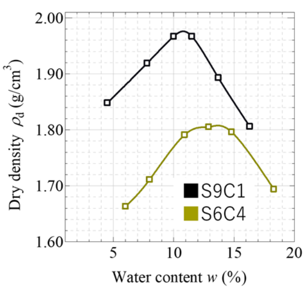

Figure 2. Compaction curve of base material.

2.2 *Preparation of soil mixed with wood chips*

Soils with wood chips were prepared by mixing the amounts of wood chips described in Section 2.1 into the base materials adjusted to their optimum water content. Test specimens were fabricated by compacting the mixed soils with a diameter of 5 cm and a height of 10 cm. The degree of compaction (Dc) was set so that the soil portion excluding wood chips reached 95%.

2.3 *Enhanced decay of wood chips through burial in a fungus cellar*

The specimens were buried in the leaf mold layer of a fungus cellar providing optimal conditions for the proliferation of wood-decay fungi in Kyoto University, as shown in Figure 3. Although it varies depending on conditions, it is said that wood decay progresses at a rate 3 to 5 times faster than under natural conditions.

Figure 3. Fungus cellar.

2.4 *Test procedures*

The specimens were buried in the fungus cellar and taken out after 3, 9, and 20 months. The consolidated undrained triaxial test ($\overline{CU}$ test) was conducted in accordance with JGS 0523-2009. The consolidation process was carried out under an isotropic pressure of 100 kPa, and the shear process was strain-controlled with an axial strain rate of 0.014%/min. Prior to shearing, the double suction and back pressure saturation method were applied to ensure that the B-value was 95% or higher. After the test, wood chips were extracted from the specimens carefully. The wood chips were then oven-dried for 24 hours to measure their dry weight. The wood chip retention rate was calculated by comparing the dry weight to the initial weight of wood mixed into the specimens.

3 TEST RESULTS

3.1 *S9C1 at dry weight ratios of 1.5%*

Figure 4 shows the results of $\overline{CU}$ test on S9C1 specimens with a wood chip content of 1.5% for burial periods up to 20 months. From the relationship between deviator stress q and axial strain ε_a, it was observed that up to 3 months of burial, the specimens exhibited higher q_{max} than the original soil without wood chips. This is partly due to a mechanism similar to that of reinforcement inclusion. According to the $q - p'$ relationships, the specimen with shorter burial periods showed an increase in q with increasing p'. As the burial period increased, the degree of plastic expansion decreased, and the specimen buried for 20 months exhibited softening behavior accompanied by plastic compression.

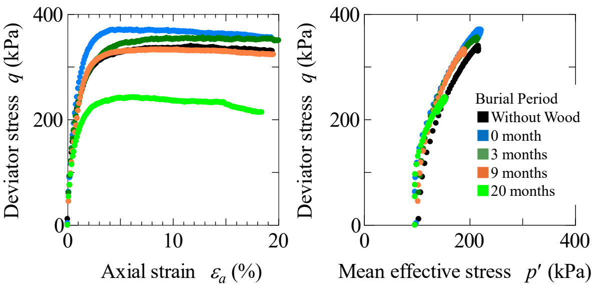

Figure 4. Triaxial compression test (S9C1 wood chip content 1.5%).

Figure 5 shows the relationship between wood chip retention rate and burial period. The retention rate decreased with longer burial periods. The series of triaxial test behaviors are considered to reflect the progressive decay of wood chips during burial, resulting in an increase in the specific volume of the specimen as shown in Table 2, and subsequent shearing under these conditions.

Based on these experimental trends, it can be inferred that at around 3 months of burial, the specimens exhibit higher *strength* than the original soil, and since this corresponds to approximately 9 to 15 months in real time, such materials have potential for use as temporary restoration ground materials. On the other hand, at a burial period of 20 months, even specimens retain sufficient *strength* as ground materials. This suggests that by mixing appropriate stabilizers as needed, these materials could potentially be used as reconstruction resources in public works.

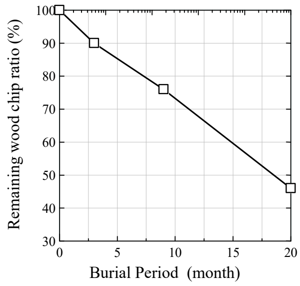

Figure 5. Relationship wood chip retention rate and burial period.

3.2 *S6C4 at dry weight ratios of 1.5%*

Figure 6 shows the results of $\overline{CU}$ test on S6C4 specimens with a wood chip content of 1.5% for burial periods up to 20 months. From $q - \varepsilon_a$ relationships, softening behavior with plastic compression was observed regardless of the burial period, and the degree of plastic compression, the q_{max}, and residual strength remained nearly constant.

According to Figure 7, the retention rate decreased from the early stages of burial. This is likely due to the high fine particle content and high water retention capacity of the soil, which promote the progression of wood chip decay. As a result, the specific volume increased with burial period, as shown in Table 4. However, the q_{max} remained nearly unchanged regardless of the burial period. This suggests that wood chip decay may not only increase the specific volume of the base soil but also that the activity of decay fungi in the soil may somehow influence cementation between soil particles.

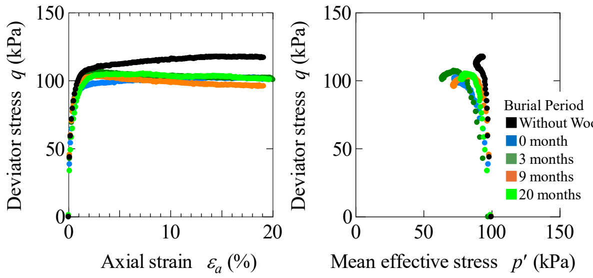

Figure 6. Triaxial compression test (S6C4 wood chip content 1.5%).

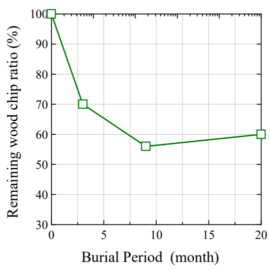

Figure 7. Relationship wood chip retention rate and burial period.

4 REPRODUCIBILITY ANALYSIS AND INTERPRETATION BASED ON SOIL SKELETON STRUCTURE CONCEPT

4.1 *Overview of SYS Cam-clay model and representation of soil with wood chip*

The SYS Cam-clay model (Asaoka et al., 2012) is an elasto-plastic constitutive model that soil skeleton structure (structure, overconsolidation and anisotropy) is introduced to the modified Cam-clay model. The model can describe the behavior of not only naturally deposited clay but also sand with any density.

Figure 8 shows the results of oedometer test on remolded and naturally deposited clay. The naturally deposited clay can exist above the normal consolidation line (NCL) of the remolded clay. This 'bulky' is defined as "structure," and a soil with a high structural state refers to one that maintains a larger specific volume under the same stress conditions. By incorporating changes in the degree of structure, overconsolidation, and anisotropy with plastic deformation, the model can reproduce a wide range of mechanical behaviors observed in clays, sands, and other soils.

The initial structure $1/R_0^*$, overconsolidation $1/R_0$, and evolution parameter a, susceptibility to degradation of structure were focused on in this study.

Reproduction calculations of shear behavior in $\overline{CU}$ tests were conducted using SYS Cam-clay model. The results for S9C1 (wood chip content: 1.5%) and S6C4 (wood chip content: 1.5%) are presented in this chapter.

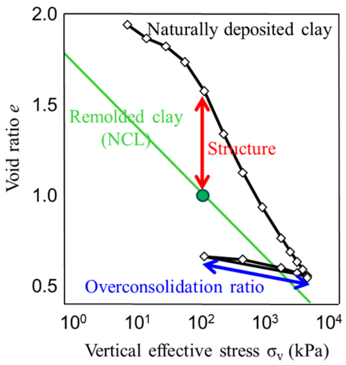

Figure 8. Oedometer test- structure and overconsolidation-.

4.2 *Calculation result of S9C1 at dry weight ratios of 1.5%*

The reproduction results for the test S9C1 shown in Figure 4 are given in Figure 9, and the material constants obtained are shown in Tables 1 and 2. As the burial period increases, the specific volume increases due to wood chip decay, which leads to an increase in the degree of structure $1/R_0^*$. In addition, the degree of hardening with plastic expansion decreases, and the q_{max} becomes smaller. This is because the overconsolidation ratio decreases, making plastic expansion more difficult to occur. From the $q - \varepsilon_a$ relationship, softening behavior in the latter stage of shearing was observed as the decay progressed. This is attributed to loss of structure due to decay of wood chips. In particular, the increasing degree of softening in the latter stage of shearing was interpreted as being due to the increase in the evolution parameter a, meaning that structures were more susceptible to degradation.

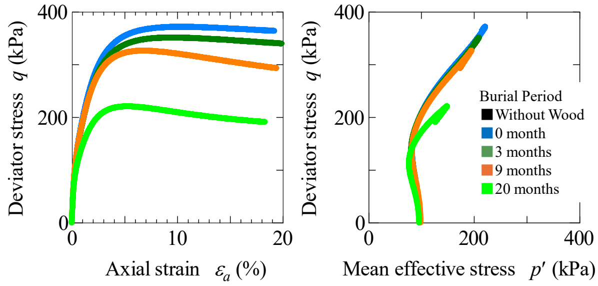

Figure 9. Oedometer test- structure and overconsolidation-.

Table 1. Material constants of S9C1 (wood chip content: 1.5%).

Elasto-plastic parameters		
Compression index	$\tilde{\lambda}$	0.14
Swelling index	$\tilde{\kappa}$	0.01
NCL intercept (at p' = 98.1 kPa)	N	1.50
Poisson's ratio	ν	0.05
Evolution parameters		
Normal consolidation index	m	3.00
Ratio of $\lVert \mathbf{D}_s^p \rVert$ to $-D_v^p$	c_s	0.50
Rotational hardening index	b_r	1.00
Rotational hardening limit constant	m_b	0.35

Table 2. Material constants M and a, and their initial values for S9C1 (wood chip content: 1.5%) at each burial period.

Material constants M and a			
Burial period (month)	Critical state Index M		Structure decay Index a
0	1.64		0.65
3	1.64		0.65
9	1.64		0.65
20	1.46		1.50
Initial values			
Burial Period (month)	Specific volume v_0	Structural degree $1/R_0$*	OCR $1/R_0$
0	1.340	1.30	4.3
3	1.352	1.35	4.2
9	1.392	1.80	4.0
20	1.419	1.86	3.5

4.3 *Calculation result of S6C4 at dry weight ratios of 1.5%*

The reproduction results for the test S6C4 shown in Figure 6 are presented in Figure 10, along with the material constants obtained in Tables 3 and 4. The increase in specific volume due to the progression of wood chip decay leads to a greater initial structure. However, the fact that the q_{max} does not change significantly with the progression of wood chip decay was reproduced by the small variation in the parameter a, meaning that the structure was less prone to degradation during shearing compared to S9C1, and by the relatively small change in the overconsolidation ratio. This is considered to represent the activity of decay fungi hypothesized in Section 3.2.

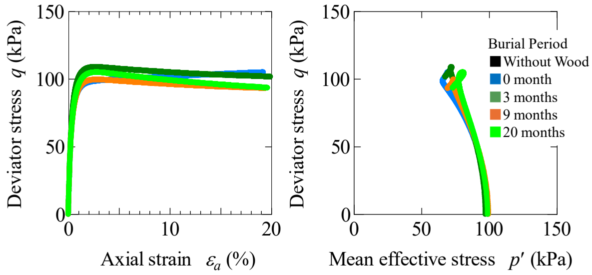

Figure 10. Oedometer test- structure and overconsolidation-.

Table 3. Material constants of S6C4 (wood chip content: 1.5%).

Elasto-plastic parameters		
Compression index	$\tilde{\lambda}$	0.17
Swelling index	$\tilde{\kappa}$	0.02
NCL intercept (at p' = 98.1 kPa)	N	1.50
Poisson's ratio	v	0.05
Evolution parameters		
Normal consolidation index	m	10.00
Ratio of $\lVert \mathbf{D}_s^p \rVert$ to $-D_v^p$	c_s	0.20
Rotational hardening index	b_r	0.10
Rotational hardening limit constant	m_b	0.50

Table 4. Material constants M and a, and their initial values for S6C4 (wood chip content: 1.5%) at each burial period..

Material constants M and a		
Burial period (month)	Critical state Index M	Structure decay Index a
0	1.50	0.65
3	1.50	0.65
9	1.34	0.80
20	1.28	0.80

Initial values			
Burial Period (month)	Specific volume v_0	Structural degree $1/R_0$*	OCR $1/R_0$
0	1.509	1.50	1.3
3	1.550	2.07	1.5
9	1.555	2.20	1.5
20	1.553	2.37	1.7

5 CONCLUSIONS

In this study, the following conclusions were obtained.

1) Relationship between the wood chip retention rate and burial duration: As the burial period increased, the wood chip retention rate decreased owing to progressive decay. The advancing decay altered the shear behavior observed in $\overline{CU}$ test.
2) In the case of S9C1 with a wood chip content of 1.5%, the q_{max} increased compared to the original soil without wood chips when the burial period was up to 3 months. The specimen with shorter burial periods exhibited an increase in q with increasing p', indicating hardening behavior with plastic expansion. On the other hand, as the burial period increased, the degree of plastic expansion decreased. The specimen buried for 20 months exhibited a transition to softening behavior with plastic compression. Reproduction analyses using the SYS Cam-clay model suggested that as the burial period lengthens, the degree of soil structure increases, overconsolidation ratio decreases, and structures tend to degrade more easily.
3) In the case of S6C4 with a wood chip content of 1.5%, softening behavior with plastic compression was observed regardless of the burial period. The degree of plastic compression, the q_{max}, and residual strength remained nearly constant. Reproduction analyses using the SYS Cam-clay model indicated that the progression of wood chip decay led to an increase in the specific volume of the specimen, thereby resulting in a larger initial soil structure. However, the fact that the q_{max} did not vary significantly despite the progression of decay was interpreted as that the structure in S6C4 is less prone to degradation during shearing compared to that in S9C1, and the change in overconsolidation ratio is relatively small.

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