An interpretation of thermo-mechanical behaviour of peat under 1-D compression

Taishi Kochi[1#], *Satoshi* Nishimura[2], and *Nobutaka* Yamazoe[3]

[1]*Hokkaido University, Graduate School of Engineering, Kita-13 Nishi-8, Kita-Ku, Sapporo, Japan*
[2]*Hokkaido University, Faculty of Engineering, Kita-13 Nishi-8, Kita-Ku, Sapporo, Japan*
[3]*Akita College, Department of Civil Engineering and Architecture, National Institute of Technology, 1-1, Iijima-Bunkyo-Cho, Akita, Japan*
[#]*Corresponding author: kouchi.taishi.h8@elms.hokudai.ac.jp*

ABSTRACT

The one-dimensional thermo-mechanical behaviour of two peats was investigated through consolidation tests, including incremental loadings and constant-rate-of-strain loadings, under a variety of temperature-stress conditions. As an appropriate expression of highly compressible materials, the natural strain was employed instead of conventional engineering strain, which eliminates the apparent stress dependency of the compression index and the coefficient of secondary compression. Test results suggest the applicability of an isotach approach to the two peats used in this study. The temperature dependency of the coefficient of secondary compression defined with natural strain, λ_α^*, is very small. All the results summarized on the effective stress-strain plane show that there exists a unique Normal Compression Line (NCL) corresponding to each combination of temperature and strain rate. The NCLs are parallel to each other. Finally, in an attempt to construct a constitutive model, the temperature dependency of the NCL was quantified by introducing a constant, λ_T^*. By using the two parameters, λ_α^* and λ_T^*, which describe the strain rate- and temperature-dependent characteristics, respectively, a 1-D thermo-mechanical behaviour observed in this study will be modelled in a simple manner.

Keywords: peats; thermal compression; natural strain; isotach.

1. Introduction

Peats consist mainly of decomposed plants with a lesser amount of inorganic soils. Since the solid parts made of decayed plants have a hollow cylindrical structure (Mesri and Ajlouni 2007), their water content is larger than that of more typical geomaterials such as clays; Hence, peats constitute significantly soft grounds. The peculiarity of peaty ground has also been indicated from the laboratory observations, namely, distinct values in mechanical parameters including much higher values of the compression index, typically defined as $C_c = \Delta e/\Delta \log\sigma_z'$ (e: void ratio, σ_z': the effective vertical stress) and C_α/C_c, the ratio of the coefficient of secondary compression, $C_\alpha = \Delta e/\Delta \log t$ (t: the elapsed time), to C_c. The high compressibility (i.e. high values in C_c) results in a substantial reduction in void ratio during the primary consolidation, leading to a large decrease in permeability (Tanaka et al. 2019, Yamazoe et al. 2020). The remarkable viscosity, (i.e. high C_α/C_c values) further complicates the consolidation behaviour of peats. The above-mentioned characteristics of peats give rise to the discrepancy of its consolidation behaviour from Terzaghi's 1-D consolidation theory, and therefore, peats have often been considered as 'unusual' soil in practice.

Recent studies revealed that soil-water coupled analysis, taking into account the change in the coefficient of permeability and isotach viscosity could produce a precise prediction of peats' consolidation behaviour observed in situ (Yamazoe et al., 2011, 2017, 2020). The isotach approach was first proposed by Šuklje (Šuklje, 1957) and relevant studies have been conducted to establish an accurate interpretation of time-dependent behaviour mainly of clayey soils (Imai and Tang 1992, Hawlader et al. 2003, Watabe et al. 2012). From the comparison of the findings from the research regarding clays and the discussion made in the recent work for peats (Yamazoe et al., 2011, 2017, 2020), it is concluded that the viscoplastic behaviour of peats can be macroscopically interpreted in the same manner as with typical inorganic soils such as clays.

Contrary to the development in studies of viscoplastic characteristics of peats, the thermo-mechanical behaviour of peats has not been carefully examined while plenty of studies on that of clayey soils have been made (Mitchell 1969, Plum and Esrig 1969, Houston et al. 1985, Hueckel and Baldi 1990, Abdullah et al. 1997, Cui et al. 2000, Cekerevac and Laloui 2004, Tsutsumi and Tanaka 2012, Kurz et al. 2016, Li et al. 2018). To the best of our knowledge, the number of research work discussing peats' thermo-mechanical behaviour is very limited (Fox and Edil, 1996, Oikawa and Ogino 2002) and the conclusions drawn by them are inconsistent with each other at least partly, and with the generally understood thermos-mechanical behaviour of clayey soils. For example, the interpretation that the coefficient of secondary compression may change with the increase of stress or temperature is controversial.

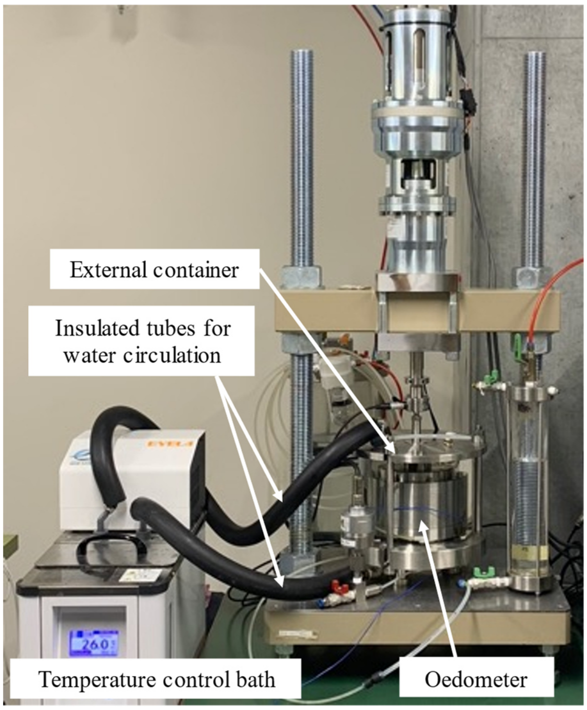

Figure 1. CRS test with the temperature control device comprised of an external container for an oedometer and temperature control bath.

Due to recent attempts to accelerate the use of local energy resources, the thermo-mechanical behaviour of soils is becoming more important. This study aims to contribute to the development in understanding the thermo-mechanical behaviour of peats. A rational and comprehensive interpretation of the thermo-mechanical behaviour of peats will be given in this paper based on the isotach approach, which will help establish an appropriate constitutive model for peats.

2. Tested materials

In this study, two different types of peats, Nakajurin and Kitamura peats, were used for experiments on thermo-mechanical behaviour. Table 1 shows their engineering properties. Sample blocks were taken from 1-2m below the ground level (the groundwater table was usually 0-0.5m below the ground level) by vertically hammering cylindrical acrylic tubes with a tapered edge (inner diameter = 76 mm, height = 140 mm and thickness = 4 mm) into the soil. To avoid exposure to sunlight and air, the tubes were sealed air-tight and covered with aluminium foil. They were kept in a 25ºC room whose temperature change was small. Specimens for consolidation tests (diameter = 75 mm, height = 25~28 mm) were obtained by horizontally cutting the block samples off.

Table 1. Engineering properties of peat samples

	Water content $w_i[\%]$	**Ignition loss** $L_{ig}[\%]$	**Density of solid part** $\rho_s[g/cm^3]$
Nakajurin	630-740	94-96	1.56-1.58
Kitamura	190-330	25-35	2.01-2.20

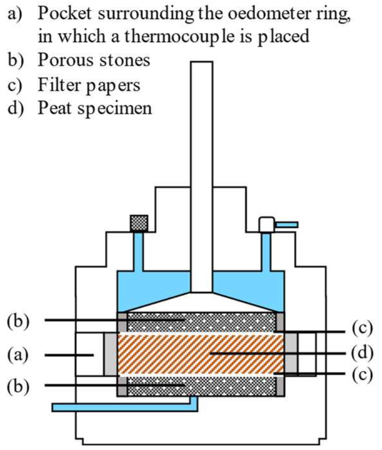

Figure 2. Schematic view of oedometer.

3. Temperature controlled test

3.1. Equipment

Tests were carried out using two systems, both of which have a similar capability to control temperature. Fig. 1 shows one of them composed of an external container for a closed cell type oedometer (Fig. 2), and a temperature control bath with a pumping function. The temperature change of a specimen in the oedometer was indirectly done by circulating water from a temperature control bath into the external container through insulated tubes. In the other system, an oedometer was simply placed in an incubator and the temperature change of a specimen was obtained indirectly by the temperature control function of the incubator.

The types of tests performed are the incremental loading consolidation test (IL test) and the constant−rate-of-strain loading consolidation test (CRS test). For IL tests, both systems were used. The temperature was measured with a thermocouple placed on the outer surface of the oedometer ring. The excess pore water pressure was measured at the bottom surface of specimen, u_{bottom}, in several test cases. For CRS tests, the system shown in Fig. 1 was used. The back pressure of 100kPa was applied for better saturation of specimen only in the CRS tests.

The change in temperature results in the deformation of the whole system, such as the thermal strain of oedometer and sensor. The influence of thermal strain of oedometer on the device is neglected assuming the change in the stress state of specimen, happened compensating the thermal strain of oedometer, is very small compared to the deformation of specimen. The temperature effect on displacement measurements was checked by heating and cooling of the whole system without a specimen in place; The offset from a reference value without a specimen in place was -0.016 ~ +0.03 mm during heating and cooling. Therefore, the temperature effect on sensor is neglected as well.

3.2. Test program

In this study, consolidation tests under a variety of thermo-mechanical conditions were applied for careful examination of the influence of temperature-stress

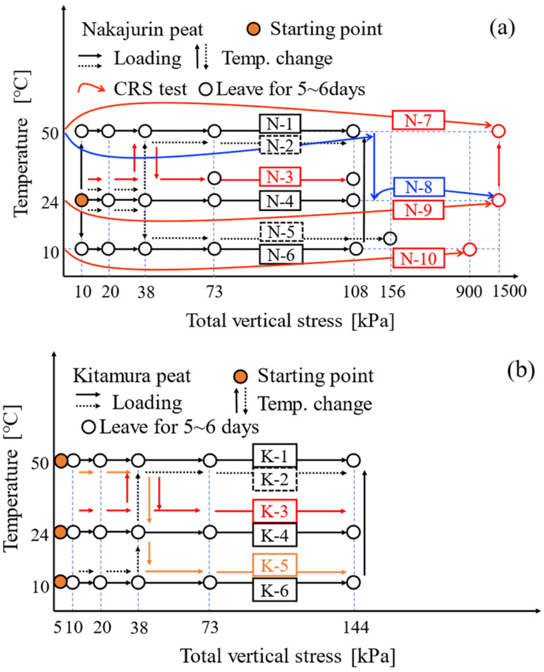

Figure 3. Thermo-mechanical paths.

Table 2. CRS test conditions

Test No.	Final total vertical stress[kPa]	Temp. [°C]	Engineering strain rate $\dot{\varepsilon}_v$ [/sec]
N-7	1500	50	5.0×10^{-6}
N-8	37	50	5.0×10^{-6}
	50		5.0×10^{-7}
	100		5.0×10^{-6}
	107		5.0×10^{-8}
	1500	24	5.0×10^{-6}
N-9	1500	24	5.0×10^{-6}
N-10	900	10	5.0×10^{-6}

history on peats' thermo-mechanical behaviour. The temperature sets were 10, 24 and 50°C. For the IL tests, the vertical stress was applied incrementally as 10-20-38-73-108kPa for Nakajurin peat and as 5-10-20-38-73-144kPa for Kitamura peat as shown in Fig. 3(a) and (b).

The stress stage of 156kPa was added only in the case of N-5. A temperature change was made during secondary compression. After each mechanical or thermal loading, compression was recorded until the compression rate reached a predefined value.

In the CRS test series, the control variable was the engineering volumetric strain rate, $\dot{\varepsilon}_v$, defined as $\varepsilon_v = \Delta H / H_{\mathrm{init}}$ where ΔH is the displacement from the initial specimen height and H_{init} is the initial height. Table 2 summarizes the test conditions of CRS tests. After the total stress reached its predefined maximum value, the total stress was fixed to the value to observe creep at the high-stress level.

3.3. Determination of the effective stress

In the CRS tests, the effective vertical stress, σ_z', was calculated by Eq. (1) as a mean value since the distribution of excess pore water pressure (=EPWP) is theoretically parabolic when the strain rate is constant.

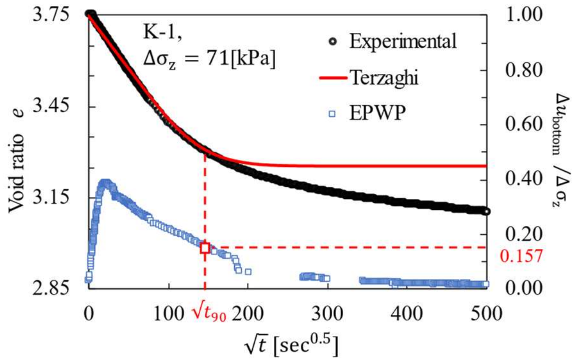

Figure 4. The typical response of Kitamura peat against mechanical loading and the estimated volume reduction from Terzaghi's theory.

$$\sigma_z' = \sigma_z - \frac{2}{3}\Delta u_{\mathrm{bottom}} \tag{1}$$

where σ_z is the total vertical stress and $\Delta u_{\mathrm{bottom}}$ is the EPWP at the bottom surface of specimen. Note that Eq. (1) is available only when the following equation is satisfied, considering the nonlinearity of the effective stress-strain relationship of soils, according to ASTM International Standards (2008).

$$\frac{\Delta u_{\mathrm{bottom}}}{\sigma_z} \leq 0.6 \tag{2}$$

where σ_z is the total stress.

In the IL tests, the effective stress was, if necessary, determined by Eq. (1) because the observations in this study matched well Terzaghi's 1-D consolidation theory. This is contrary to the general view that the theory cannot apply to peats. An approximate solution of Terzaghi's theory can be gained by assuming a parabolic distribution of EPWP (Atkinson and Bransky 1977). Fig. 4 shows a typical mechanical response of Kitamura peat to a load increment and its simulation by Terzaghi's theory. The void ratio change, Δe, is calculated as:

$$\Delta e(t) = (1 + e_0) m_v U(t) \Delta\sigma_z \tag{3}$$

where e_0 is the initial void ratio, $m_v = \partial\varepsilon_v / \partial\sigma_z' = const.$ and $U(t)$ is the average degree of consolidation derived from Terzaghi's theory as a function of time, t.

For the calculation of $U(t)$, c_v is determined from t_{90}, the time corresponding to 90% average consolidation degree, at which the value of $\Delta u_{\mathrm{bottom}} / \Delta\sigma_z$ is approximately 0.157 according to Terzaghi theory. From Fig. 4, it is obvious that the experimental result follows Terzaghi's theory well. This is probably because the load increment was smaller than in the typical construction in the IL tests performed, and therefore, the change in c_v, or the decrease in the hydraulic conductivity which exceeds that of m_v, may have been less significant. A similar discussion has been made by Tanaka et.al. (Tanaka et.al. 2019). Regarding Nakajurin peat, the dissipation of EPWP was rapid enough not to matter in computing the effective stress by Eq. (1) for the discussion in this paper. Note that the water pressure transducer did not respond instantly after the mechanical loading due to the compliance of the whole experiment system, including that of the oedometer and the sensor itself. Therefore, the value of EPWP before its peak was not used for the calculation of Eq. (2).

4. Definition of strain

It has been pointed out that the linearity of $\varepsilon_{\mathrm{v}} - \log\sigma_z'$ curve does not hold when large compression occurs (Butterfield, 1979; Oikawa, 1987) and this may cause a problem when determining the compression index. To avoid such a problem, the natural volumetric strain, $\varepsilon_{\mathrm{nv}}$, defined as;

$$\varepsilon_{\mathrm{nv}} = \int_{H_{\mathrm{init}}}^{H} \frac{dH}{H} = -\ln\left(1 - \varepsilon_{\mathrm{v}}\right) \tag{4}$$

is employed instead of the engineering strain, ε_{v}. Fig. 5 shows that, when the natural strain is employed, the linearity holds over the entire normal compression range. Also, the stress-dependency of the coefficient of secondary compression is eliminated. As shown in Fig. 6, while the slope at the end of each orange curve, namely, $2.303\lambda_{\alpha\varepsilon}$ ($\lambda_{\alpha\varepsilon} = -\Delta\varepsilon_{\mathrm{v}}/\Delta\ln\dot{\varepsilon}_{\mathrm{v}}$), decreases from 0.029 to 0.012 with the accumulation of strain, the slope at the end of each blue curve, $2.303\ \lambda_{\alpha}^{*}$ ($\lambda_{\alpha}^{*} = -\Delta\varepsilon_{\mathrm{nv}}/\Delta\ln\dot{\varepsilon}_{\mathrm{nv}}$), remains unchanged; The value is 0.006 for each case. This is in support of usefulness of $\varepsilon_{\mathrm{nv}}$ as a quantity to describe the volume change of peats, along with the linearity of compression curve. Hereafter, mechanical parameters defined for $\varepsilon_{\mathrm{nv}}$ are described with asterisk to distinguish from conventional counterparts.

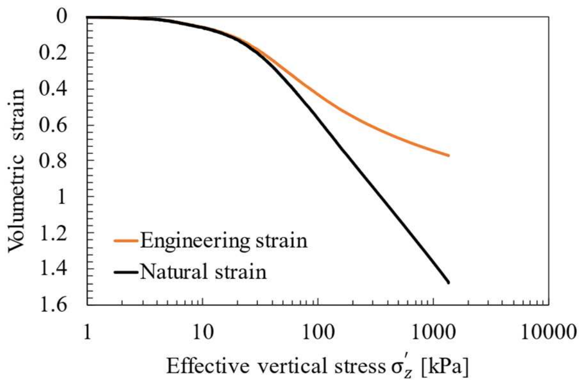

Figure 5. The stress-strain relationship obtained from N-9 plotted against both the engineering and natural strain.

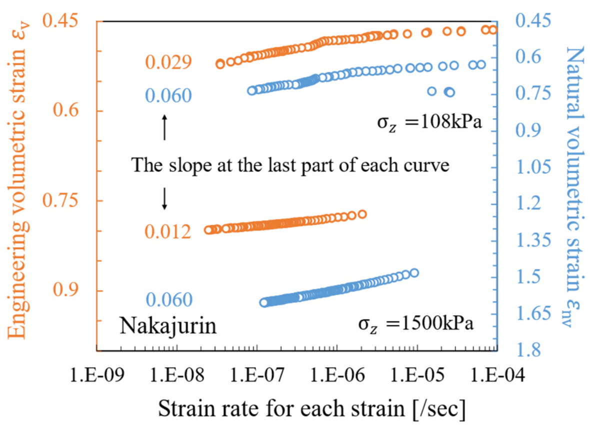

Figure 6. The strain-strain rate relationship at the typical stress level (σ_z=108kPa from N-4) and the extremely high-stress level (σ_z=1500kPa from N-9).

5. Test results

5.1. Isotach behaviour of peats

According to the isotach law, the stress-strain relationship of soils changes with the visco-plastic strain rate. By differentiating Eq. (4) with time *t*, the following relationship is gained;

$$\dot{\varepsilon}_{\mathrm{nv}} = \dot{\varepsilon}_{\mathrm{v}}/(1 - \varepsilon_{\mathrm{v}}) \tag{5}$$

This suggests that $\dot{\varepsilon}_{\mathrm{nv}}$ increases with the accumulation of ε_{v} in the CRS tests performed, where $\dot{\varepsilon}_{\mathrm{v}}$ was the control variable. The maximum value of ε_{v} within the stress range shown in Fig. 7 is about 0.58, and the change in $\dot{\varepsilon}_{\mathrm{nv}}$ is 2.38 times of $\dot{\varepsilon}_{\mathrm{v}}$ according to Eq. (5).

This accelerating natural strain rate partly explains the rightward shift of the final part of the effective stress-strain relationship shown in Fig. 7 (red line). Nevertheless, the discussion on Fig. 7 will be made under the assumption that $\dot{\varepsilon}_{\mathrm{nv}}$ is the same as $\dot{\varepsilon}_{\mathrm{v}}$. The total strain rate $\dot{\varepsilon}_{\mathrm{nv}}$ is used as a state variable to describe the viscous behaviour of soils although the visco-plastic strain rate is preferable as a precise description. This is because the precise estimation of the elastic strain rate, or the swelling index, is difficult and the proportion of elastic strain rate to the total strain rate is assumed to be small.

Fig. 7 shows the effective stress-strain relationship of two peats, obtained from N-8 (red line) and K-1 (black plots). For both cases, the strain rate-dependent normal compression lines, NCLs, are identified suggesting the applicability of isotach law to Nakajurin and Kitamura peat. Note that some of the black plots are obtained by using Eq. (2) where the EPWP had not completely dissipated. The gap between the adjacent two isotach lines, $\Delta\varepsilon_{\mathrm{nv}}^{\mathrm{vp}}$, is equivalent to the amount of creep occurring while the strain rate decreases by a factor of 10, or, $\Delta\varepsilon_{\mathrm{nv}}^{\mathrm{vp}} = -\Delta\varepsilon_{\mathrm{nv}}^{\mathrm{vp}}/\Delta\log\left(0.1\dot{\varepsilon}_{\mathrm{nv}}/\dot{\varepsilon}_{\mathrm{nv}}\right) = 2.303\,\lambda_{\alpha}^{*}$. For K-1, $2.303\lambda_{\alpha}^{*} = 0.040$ is obtained as shown in the figure. This value is quite close to the ones gained as a slope of the last part of $\varepsilon_{\mathrm{nv}} - \log\dot{\varepsilon}_{\mathrm{nv}}$ curve, for instance, as the one seen in Fig. 8(b). Under the assumption that λ_{α}^{*} is the material parameter which determines the isotach viscous behaviour, this agreement in λ_{α}^{*} suggests the EPWP estimation by Eq. (2) is valid.

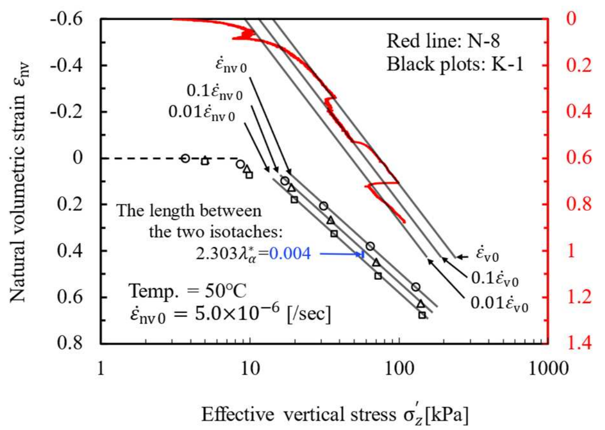

Figure 7. The isotach behaviour of peats, data from N-8 and K-1.

5.2. Creep and thermal compression behaviour

The previous studies by Fox and Edil (1996) and Oikawa and Ogino (2001) revealed that peaty soils exhibit a large amount of settlement after heating compared with other geotechnical materials. However, detailed, time-dependent thermo-mechanical behaviour of peats does not seem to have been attained yet. A debatable interpretation made among these papers is that the coefficient of secondary compression is dependent on temperature, which comes from observation of the sudden change in the slope of volume change-logarithmic of time curve (e.g. e-log$t$ curve) after heating, as can be seen in the points indicated by arrows in Fig. 8. This is obviously because of the way the elapsed time is measured. We believe that the coefficient of secondary compression is rather a material parameter which represents the viscous characteristics of soil within the normal compression range and it should not be changeable with the way of measuring time. As indicated by the blue plots in Fig. 8, such a drastic change in the slope is eliminated if the strain is plotted against the strain rate. Accordingly, λ_α^* is determined as $-\Delta\varepsilon_{\mathrm{nv}}/\Delta\ln\dot{\varepsilon}_{\mathrm{nv}}$ in this study. Fig. 8 also suggests that the λ_α^* is a constant irrelevant to temperature and the similar result is actually available in the reference (Fox and Edil, Fig. 9(a) and (c), 1996). Note that, in the case of Kitamura peat (Fig. 8(b)), the EPWP was generated during the first part of thermal compression, and therefore, the thermal compression is not totally due to creep at the beginning unlike the result of Nakajurin peat (Fig. 8(a)). Hence, the value of $-\Delta\varepsilon_{\mathrm{nv}}/\Delta\ln\dot{\varepsilon}_{\mathrm{nv}}$ at the beginning in Fig. 7(b) is not appropriate as λ_α^*. The average value of λ_α^* and $\lambda_\alpha^*/\lambda^*$ for each peat is summarized in Table 3.

Table 3. Material parameters defining the viscous characteristics, λ_α^*, and the compressibility against heating, λ_T^*, for each peat sample (Average value)

	λ_α^*	$\lambda_\alpha^*/\lambda^*$	λ_T^*	λ_T^*/λ^*
Nakajurin	0.030	0.087	0.24	0.68
Kitamura	0.017	0.074	0.16	0.70

The blue plots in Fig. 8 indicates that the different stress-strain relationship exists even at the same strain rate depending on the temperature. This behaviour apparently contradicting the isotach law can be interpreted based on the assumption that different families of isotaches are defined for different temperatures. The result of N-3, where a peat specimen underwent the first heating (24→50℃) at 38 kPa during the secondary compression and then cooling to the original temperature (50→24℃), is a good example to explain the assumption. Fig. 9, the result of N-3, clearly shows that the soil's (σ_z', $\varepsilon_{\mathrm{nv}}$) state moves down in the stress-strain space after heating, following the isotach lines redefined for 50℃, and after cooling, it approaches to the ones for the original temperature of 24℃ through the over-consolidated state. Fig. 10 summarizes all test results except the over-consolidated behaviour immediately after cooling, suggesting that a unique relationship corresponding to each temperature exists at the three different strain rates. The lines are parallel to each other, and appreciable influence of the temperature and stress history on mechanical behaviour, such as a promotion of aging effect (Tsuchida et al. 1991, Towhata et al. 1993, Tsutsumi and Tanaka 2012), is not observed. Accordingly, the stress strain relationship for the natural peats, which depends on temperature and strain rate, is schematized as shown in Fig. 11.

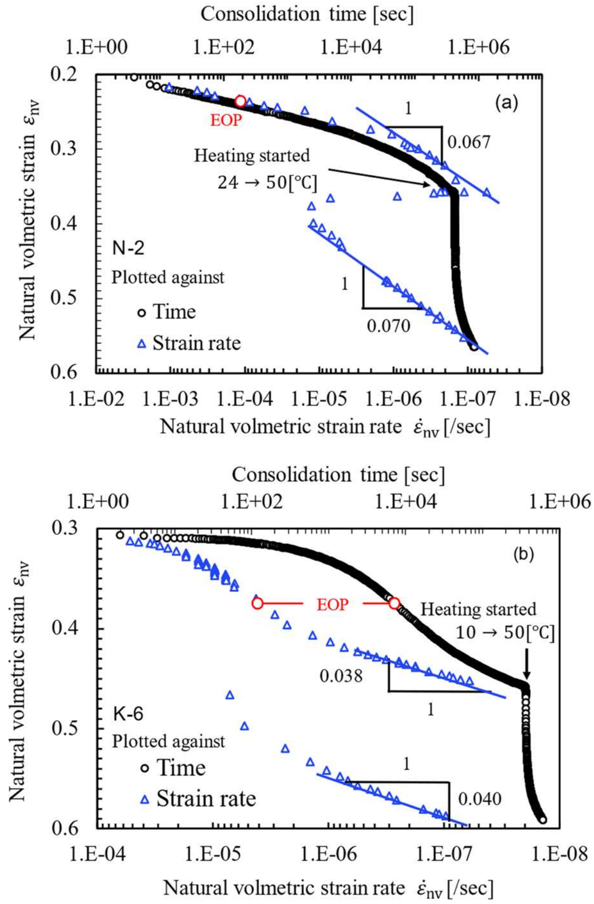

Figure 8. The typical response after heating in the middle of the secondary compression plotted against time (black) and strain rate (blue), obtained from N-2 and K-6.

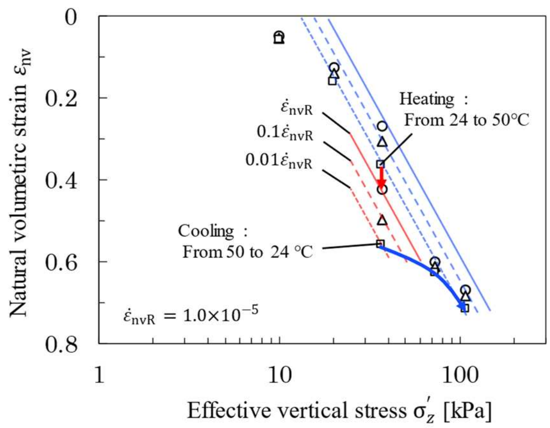

Figure 9. The stress-strain response of Nakajurin peat against cooling after heating, from N-3.

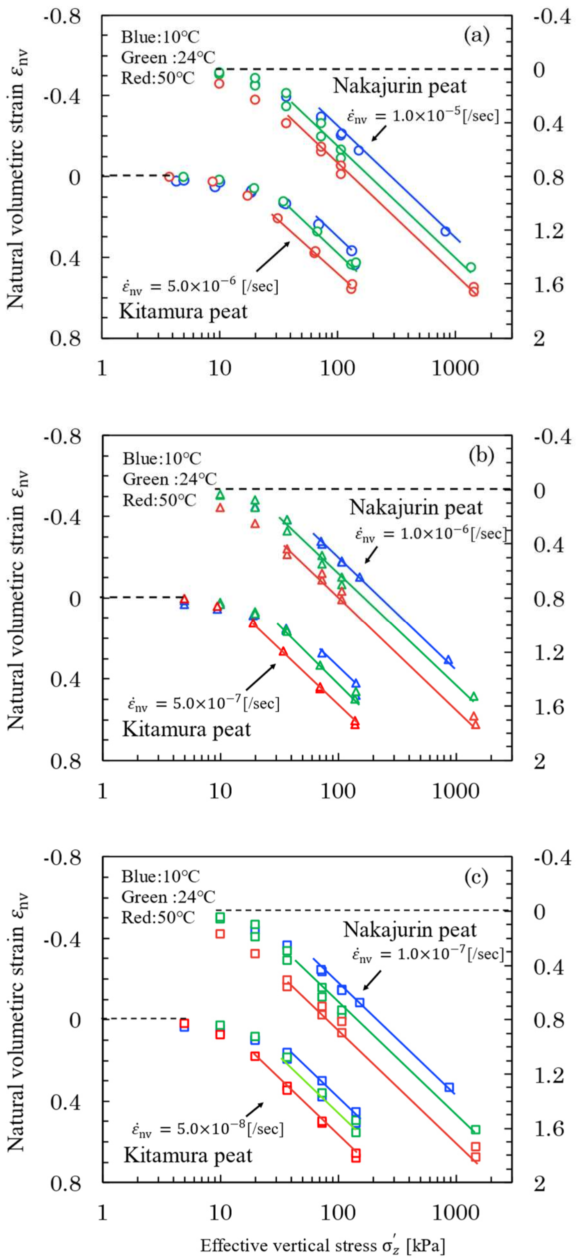

Figure 10. The stress-strain relationship obtained from all test results exhibiting the temperature dependency at three different strain rate.

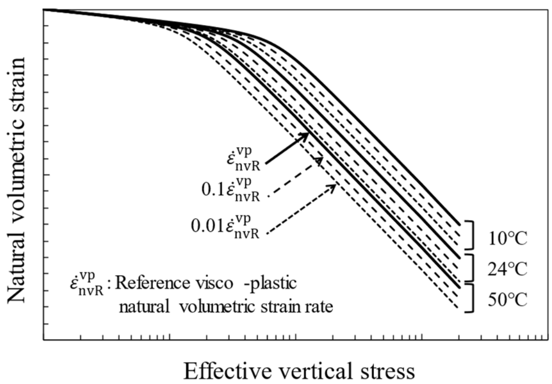

Figure 11. Schematic diagram of the strain rate –and temperature– dependent stress-strain relationship of natural peats.

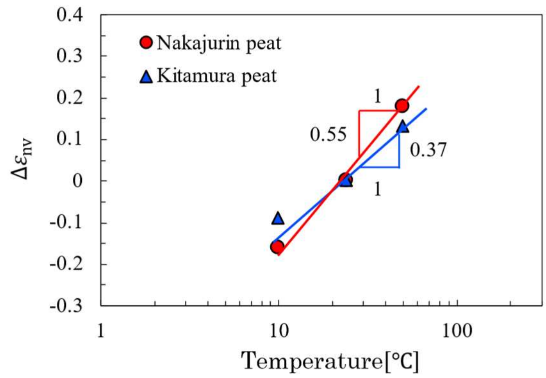

Figure 12. The offset from the NCL at 24°C, $\Delta\varepsilon_{nv}^{vp}$,with temperature change under a fixed strain rate.

In order to quantify the thermal compression behaviour, the offset from the reference NCL ($T_R = 24$[°C]) due to temperature change at the fixed strain rate, $\Delta\varepsilon_{nv}^{vp}$, is plotted against temperature in Fig. 12. The relationship, $\Delta\varepsilon_{nv}^{vp} = \lambda_T^* \ln(T/T_R)$, is found for both peats. Note that λ_T^* is a constant defining the compressibility against heating. As summarized in Table 3, the value of λ_T^* is larger for Nakajurin peat which has the larger compressibility. The similar values of λ_T^*/λ^* are obtained for both peats. We expect that the constant value of λ_T^*/λ^* holds even for other types of peats from the analogy of the constant value of C_α/C_c for peats shown by Mesri and Ajlouni (2007).

Conclusion

In this study, the consolidation tests under a variety of temperature-stress conditions were carried out for two types of peats in order to expand our knowledge of thermo-mechanical behaviour of peats. The major conclusions drawn from them are as follows;

- The coefficient of secondary compression, λ_α^*, is determined as a slope of the last part of $\varepsilon_{nv} - \log\dot{\varepsilon}_{nv}$ curve, because λ_α^* is changeable with the way the elapsed time is measured. This alternative definition, $\lambda_\alpha^* = -\Delta\varepsilon_{nv}/\Delta\ln\dot{\varepsilon}_{nv}$, results in the conclusion that λ_α^* is almost irrelevant to the temperature.
- To interpret the thermo-mechanical behaviour including the thermal compression, it is assumed that the isotach relationship should be redefined for each temperature. All the test results, which involve a variety of thermo-mechanical paths, follow the assumption.
- To quantify the characteristic of thermal compression behaviour, the offsets of the Normal Compression Line (NCL) from the NCL at 24°C, $\Delta\varepsilon_{nv}^{vp}$, were plotted against temperature. For the two peats, the relationship, $\Delta\varepsilon_{nv}^{vp} = \lambda_T^* \ln(T/T_R)$, is found. Since the similar values of λ_T^*/λ^* are obtained for two peats which have different natural water content, it can be assumed that a similar λ_T^*/λ^* value is found for other types of peats from the analogy with the constant value of C_α/C_c for peats.

The thermo-mechanical behaviour observed in this study will be reproduced by a 1-D elastic-viscoplastic model described by fundamental parameters of the compression and swelling indices, λ_α^* and λ_T^*. The discussion made in this paper is not beyond the microscopic interpretation and the understanding of the essential mechanism of thermal compression or the influence of long-term exposure of peats to unnaturally high temperatures. The Authors believe that studies from microscopic or chemical viewpoints should be conducted for further precise prediction of the long-term thermo-mechanical behaviour of peats.

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