

Temperature dependency of secondary consolidation in peats

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ABSTRACT: This study investigates the temperature dependency of secondary consolidation in peats. Oedometer tests were conducted under a variety of stress-temperature paths for three peats, which had different natural water contents (300%, 800%, and 1,100%). The applied temperature was either 10°C, 24°C, or 50°C. In this paper, the coefficient of secondary consolidation is defined against natural volumetric strain and strain rate, differing from the conventional definition using the void ratio and elapsed time. The use of natural strain helps mitigate the apparent stress dependence, which is often observed when employing the void ratio. The settlement is presented in terms of strain–strain rate rather than strain–time. This approach overcomes the drawback of time-based representation, where the curve shape is influenced by the choice of the time origin. Through careful data presentation, the test results reveal that the coefficient of secondary consolidation of peats is temperature-dependent; its ratio to the compression index is approximately 0.055 at 10°C, 0.070 at 24°C, and 0.095 at 50°C for each peat. The results at 10°C, which is close to the in-situ temperature in cold regions, and at 24°C, which approximates typical laboratory conditions, are reasonably consistent with the well-known empirical relationship by Mesri and his coworkers. This suggests that the temperature dependency presented here does not contradict existing understanding, while in cases where temperature increases significantly, it should be considered. The temperature dependency indicates that the expression for thermo-plasticity in peats, referred to as the coefficient of thermo-plastic compression, is dependent on the strain rate. This intertwined effect of strain rate and temperature is mathematically described. Also, a comparative analysis of the thermo-mechanical behaviour under constant and transient effective stress conditions supports the temperature dependency of the coefficient of secondary consolidation and emphasises its importance in the estimation of the effective stress state.

KEYWORDS: Organic soil, long-term behaviour, temperature effect.

1 INTRODUCTION

It is well known that peats exhibit large settlement after construction. While this is attributable mostly to their high compressibility, their pronounced viscosity is also of importance when considering the long-term behaviour, which often causes practical problems over the service period of infrastructure, such as the road surface unevenness (e.g., Yamazoe et al., 2023). Previous studies (e.g., Yamazoe et al., 2023; Long et al., 2023) have shown that the time-dependent behaviour of peats is well explained by the isotach theory. The theory assumes that the soil follows an identical normal compression line (i.e. NCL, or ‘isotaches’) for a given strain rate. Succinctly put, the time-dependent behaviour in peats is a unique reflection of the strain rate-dependency. The spacing between isotaches is typically determined by the coefficient of secondary consolidation, and hence, it is an essential parameter for implementing the isotach theory in more advanced models.

Attention should not only be paid to the time-dependent problems, but also to the temperature-dependent characteristics of peats. Shallow geothermal energy systems, including the energy pile, have been applied over the past few decades, primarily in European countries and, more recently, in Japan. Van Lyssevetten (2017) reported that thermal conduction from the structure induces dynamic temperature fluctuations of up to 10°C in the peat layer, occurring at a radial distance of 0.5–2.5 m. This raises concerns to potential ground settlement in soft soils. However, research on the temperature-dependency of peats had not been highlighted since the earlier works by Edil and Fox (1996) and Oikawa and Ogino (2001), leaving a knowledge gap. In light of this, the authors conducted laboratory work to examine the thermo-mechanical behaviour of peats through oedometer tests under different temperatures (Kochi et al., 2024). The key findings are as follows. [1] The plastic compression occurs after heating peats (i.e., thermo-plastic compression). The compression continues even after the thermal equilibrium has been reached, indicating the concurrent influence of viscosity. [2] The thermo-plasticity of peats was systematically characterised using a linear coefficient, referred to as the coefficient of thermo-plastic compression by the authors. [3] The simultaneous effect of strain rate and

temperature in peats can be well explained by a simple extension of isotach theory, where the NCL is strain rate- and temperature-dependent. The coefficient of thermo-plastic compression is used to space the isotherms for a given strain rate.

To advance understanding of its long-term behaviour, this paper presents experimental findings on the temperature-dependency of the secondary consolidation of peat. It includes a summary of our previous study, as well as supplementary new findings such as a strain rate-based correction for the coefficient of thermo-plastic compression, to precisely express the intertwined effect of temperature and viscosity in peats, and a comparative analysis of viscous behaviour under constant and transient effective stress conditions.

2 TESTED MATERIAL

The peats used in this study were taken from three different sites in Hokkaido, Japan. The samples are named after their sampling sites: Nakajurin, Kitamura and Teshio. They are denoted as N, K and T in test names. Each possesses a different natural water content, as shown in Table 1. In peat, the natural water content is strongly correlated with its mechanical properties (e.g., Oikawa, 1987), and therefore, investigations on samples with a wide range of water contents contributes to a better understanding of their general behaviour.

Table 1. Engineering properties of peat samples

	Natural water content w_n [%]	Ignition loss L_{ig} [%]	Density of soil particle ρ_s [kg /m ³]	Von Post scale	Initial yield stress [†] σ'_{yld0} [kPa]
Nakajurin	800-940	94-96	1,560 – 1,580	H2	12-18
Kitamura	260-340	25-35	2,010 – 2,200	H5	17-25
Teshio	1090-1170	90-91	1,380 – 1,480	H7	10-15

[†] The values vary with the temperature and strain rate. The reference here is 24°C and on the order of 10⁻⁷ to 10⁻⁸ [1/sec].

3 TEST METHODS

The temperature-dependency in secondary consolidation of peats was investigated by oedometer tests under three temperatures: 10, 24 and 50°C. In the incremental loading tests (i.e., N-, K- and T- IL tests), the loading stages of 10, 20, 37, 73 and 144 (or 107) kPa were adopted. The thermo-mechanical test paths incorporated a temperature change between certain incremental loading stages. The test path for Teshio peat is presented in Fig.1 as a representative case; similar tests were conducted for Nakajurin and Kitamura. (See Kochi et al., 2024 for the detail) to examine the influence of mechanical loading history and temperature change history on the secondary consolidation behaviour. For Teshio peat, constant load oedometer tests with relatively longer stage duration (i.e. 10days under 37kPa) were additionally performed under 10, 24 and 50°C. The multi-stage constant rate of strain consolidation tests (i.e., mCRS tests), where the strain rate changes and cooling (i.e., 10 to 24°C) were involved, were done for Nakajurin and Teshio peats, to investigate the temperature dependency of coefficient of secondary consolidation under the transient effective stress condition, in contrast to the constant effective stress condition in IL tests.

The temperature control for specimen during the tests was achieved by using either of the following two systems: [a] the oedometer placed in a sealed container, in which the water from the temperature-controlled bath was circulated; [b] the oedometer placed in an incubator with a temperature-control function. Further details for the test apparatus and method are available in Kochi et al. (2024).

4 RESULTS

The following three parameters to adequately describe the isothermal isotach concept are first introduced. Here, the natural (log) strain ε_{nv} is assumed to be decomposed into elastic and viscoplastic component, denoted as ε_{nv}^e and ε_{nv}^{vp} respectively.

Compression index:

$$\lambda^* = \frac{\partial \varepsilon_{nv}}{\partial \ln \sigma_z} \quad (1)$$

where σ_z is the effective vertical stress.

Coefficient of secondary consolidation:

$$\lambda_\alpha^* = - \frac{\partial \varepsilon_{nv}}{\partial \ln \dot{\varepsilon}_{nv}^{vp}} \quad (2)$$

where the dot indicates the time derivative.

Coefficient of thermo-plastic compression:

$$C_\beta^* = \frac{\partial \varepsilon_{nv}}{\partial T} [1/^\circ\text{C}] \quad (3)$$

where T is the temperature.

The coefficient of secondary consolidation is typically determined as a slope of settlement–log t curve (t : elapsed time). However, the curve can appear differently depending on the way the origin of t is taken. This becomes particularly significant when discussing the thermal compression of peats. Two approaches have seen in previous studies (Edil and Fox, 1996; Oikawa and Ogino, 2001): $t = 0$ for load application or $t = 0$ for subsequent heating application. To eliminate ambiguity in data interpretation, the thermal compression behaviour of peats is here analysed in terms of the volumetric strain rate, instead of t , following the definition by Eq. (2). Figs.2 (a) (b) and (c) show the thermal compression of Nakajurin, Kitamura and Teshio peats, respectively, by plotting

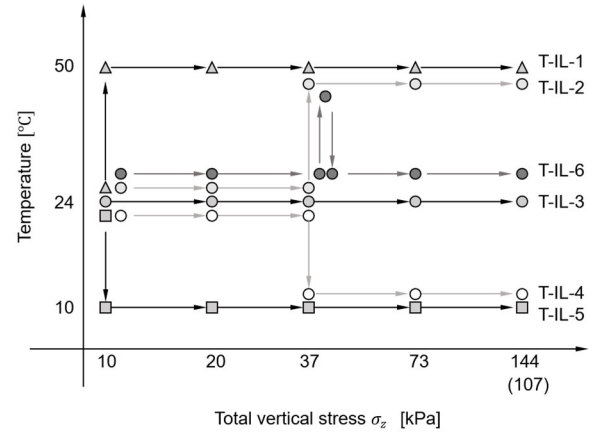


Figure 1. Representative test paths for IL test series

ε_{nv} against both t and $\dot{\varepsilon}_{nv}$, where $t = 0$ for load application. While the $\varepsilon_{nv} - \log t$ curve (solid line) exhibits a pronounced slope change before and after heating, the corresponding change in the $\varepsilon_{nv} - \log \dot{\varepsilon}_{nv}$ curve (grey markers) is rather moderate. Note that the slope of $\varepsilon_{nv} - \log \dot{\varepsilon}_{nv}$ after the end of primary consolidation (i.e., EOP) corresponds to the coefficient of secondary consolidation. Previous studies attributed the slope change in the settlement–log t curve to variations in the coefficient of secondary consolidation. However, a comparison of both curves suggests that such kinks in the settlement–log t plot do not necessarily indicate temperature dependency of the coefficient of secondary consolidation. Nevertheless, its moderate temperature dependency remains evident in the $\varepsilon_{nv} - \log \dot{\varepsilon}_{nv}$ curves, as indicated by the difference in slopes before and after heating. The long-term consolidation tests (Fig.3) also support this.

The values of coefficient of secondary consolidation obtained from various oedometer tests under different temperature conditions (See Kochi et al., 2024, for the details of tests) are summarised in Fig. 4, in the form of ratio to the compression index (i.e., $\lambda_\alpha^*/\lambda^*$). Here, the compression index λ^* is assumed to be constant based on the test results ($\lambda^* = 0.39$ for Nakajurin, 0.24 for Kitamura and 0.40 for Teshio). Note that mathematically $\lambda_\alpha^*/\lambda^* = C_\alpha/C_c$, where C_α and C_c are the coefficient of secondary consolidation and compression index, defined against void ratio and common logarithm. It shows the stress-dependency of the coefficient of secondary consolidation, typically observed when defined against void ratio, is significantly reduced when using the natural strain. Although the data exhibit some scatter, comparing the values at 10–50°C reveals that the secondary compression coefficient of each peat is temperature-dependent. For a more simplified presentation, Fig. 4(b) extracts and displays the maximum, average, and minimum values for each peat at each temperature from the same dataset. Performing a linear regression on the average where $\lambda_\alpha^*|_T$ denotes λ_α^* at temperature T , T_{ref} a reference temperature and c_T the linear coefficient to express the temperature-dependency of the coefficient of secondary consolidation. For the current data, $c_T = 0.001 [1/^\circ\text{C}]$ and $\lambda_\alpha^*|_{10^\circ\text{C}} = 0.055$. Note that the results at 10°C, which is close to the in-situ temperature in cold regions, and at 24°C, which approximates typical laboratory conditions, are reasonably consistent with the well-known empirical relationship by Mesri and his coworkers (i.e., $C_\alpha/C_c = 0.06 \pm 0.01$, Mesri and Ajlouni, 2007). This suggests that the temperature-dependency presented here does not contradict existing understanding, while, in cases where temperature increases significantly, careful interpretation of temperature-dependency becomes

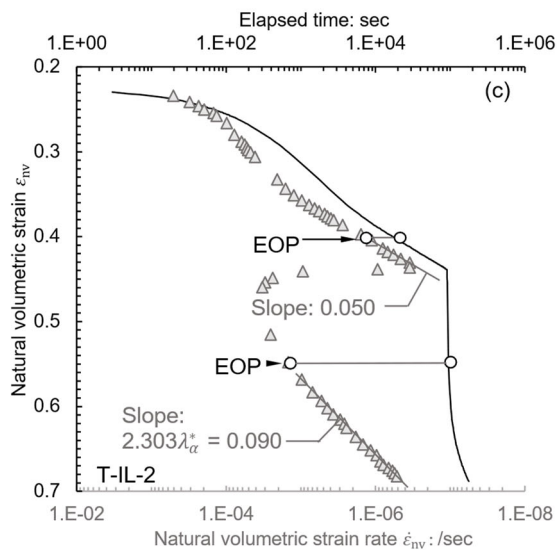
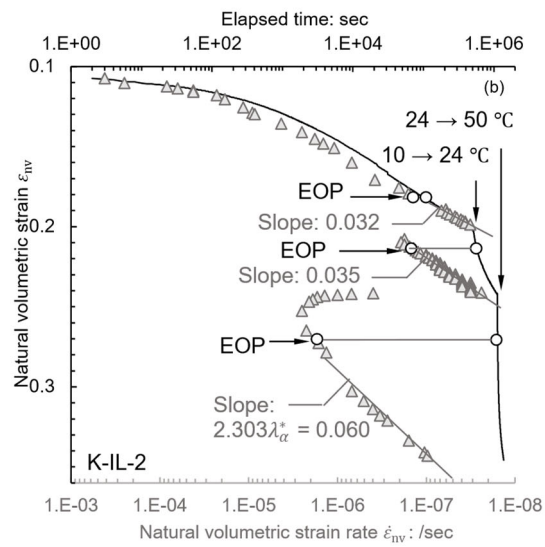
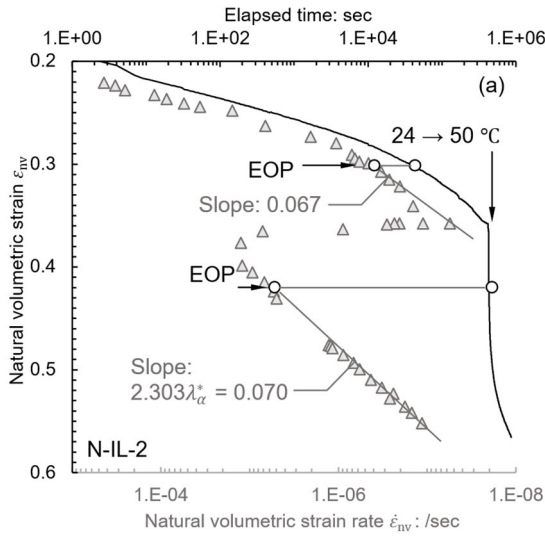


Figure 2. Secondary consolidation behaviour before and after heating at 37 kPa (a) Nakajurin (b) Kitamura (c) Teshio

Also, the temperature-dependency of the coefficient of secondary consolidation indicates that the coefficient of thermo-plastic compression C_β^* is dependent on

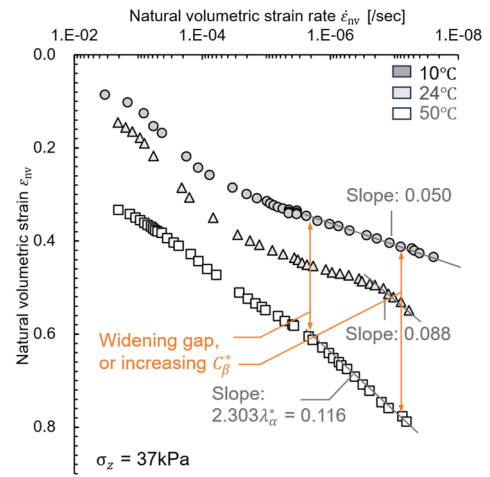


Figure 3. Secondary consolidation of Teshio peat at different temperature

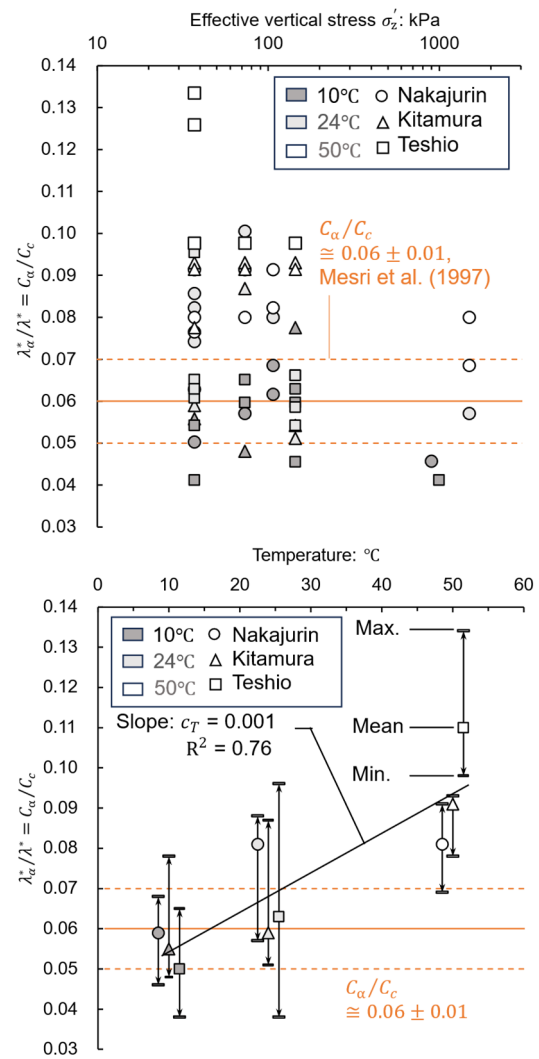


Figure 4. Ratio of coefficient of secondary consolidation to compression index plotted against (a) stress (b) temperature

the strain rate used for its determination $\dot{\epsilon}_{nv}^{vp}$ as evident in Fig. 3. This combined effect is described as follows.

$$\frac{C_\beta^*|_{\dot{\epsilon}_{nv}^{vp}}}{\lambda^*} = \frac{C_\beta^*|_{\dot{\epsilon}_{nv}^{vp}}}{\lambda^*} + c_T \ln(\dot{\epsilon}_{nv}^{vp} / \dot{\epsilon}_{nv}^{vp,ref}) \quad (5)$$

Substituting $c_T = 0.001$ [$^{\circ}\text{C}$] and $\dot{\epsilon}_{nv}^{vp}/\dot{\epsilon}_{nv,ref}^{vp} = 10$ or 0.1 , the change in the ratio, $\Delta(C_{\beta}^*/\lambda^*)$, is estimated to be 0.0023 . Given that $C_{\beta}^*/\lambda^* \cong 0.020$ under $\dot{\epsilon}_{nv}^{vp}$ on the order of $10^{-6} \sim 10^{-8}$ [sec] for various peats (Kochi et al., 2024), this corresponds to a 10% variation when the reference strain rate changes by a factor of 10 or 0.1. Considering this effect into parameter settings is essential for ensuring the accuracy of numerical analyses.

The temperature dependency of coefficient of secondary consolidation is here to be examined by mCRS test, which includes the multiple changes in strain rate and cooling (i.e., 10 to 24°C). As shown in Figs. 5 (a) and (b), the coefficient of secondary consolidation is identified from the gap between isotaches, partially observed through the strain rate shifts. Note that data presentation at the CRS stage with the highest strain rate after cooling may include inaccuracies, as the measured excess pore water pressure (i.e., EPWP) was unnaturally low (almost zero) considering the corresponding hydraulic conductivity estimated from the IL test series (i.e., on the order of 10^{-8} [m/sec]). While an incorrect setting for the water pressure transducer is suspected, this influence should be minimal at the $0.1\dot{\epsilon}_v$ and $0.01\dot{\epsilon}_v$ stages, where the strain rate is sufficiently low that no significant excess pore water pressure is generated. The data evaluation at these lower strain rate stage supports the coefficient of secondary consolidation is temperature-dependent (i.e., $\lambda_{\alpha}^*/\lambda^* = 0.060$ at 24°C , 0.049 at 10°C for Nakajurin and 0.075 at 24°C , 0.057 at 10°C for Teshio). It indicates $c_T \cong 0.010$, being consistent with the results under constant effective stress condition (Fig. 5). Careful determination of the coefficient of secondary consolidation, accounting for the temperature effect, will improve the estimation of both long-term settlement and effective stress state.

5 CONCLUSIONS

In this paper, the temperature-dependency of secondary consolidation in peats was investigated through oedometer tests under three different temperatures of 10, 24 and 50°C . The coefficient of secondary consolidation was defined against strain rate, rather than the typically used elapsed time, allowing for more objective evaluation of its value, particularly before and after heating. The test results show that the coefficient of secondary consolidation is temperature dependent. As its simple expression, a linear approximation against temperature was applied. In the framework of isotach-isotherm theory, this temperature-dependency of the coefficient of secondary consolidation means that the value of the coefficient of thermo-plastic compression is strain rate-dependent in a reciprocal manner. A suite of simple linear and log-linear equations captures these aspects sufficiently. Also, a comparative analysis of viscous behaviour under constant and transient effective stress conditions supports the temperature dependency of the coefficient of secondary consolidation and emphasises its importance in the effective stress state estimation.

6 ACKNOWLEDGEMENTS

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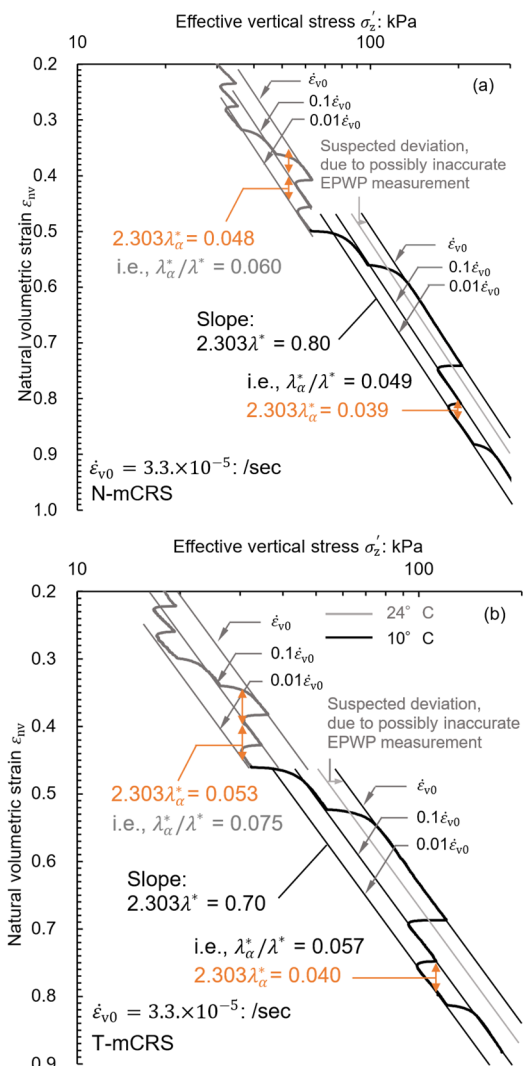


Figure 5. Results of multi-stage CRS test including shifts in strain rate and a cooling process (a) Nakajurin and (b) Teshio

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