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Experimental study and modeling on determining the predictors of creep behavior on small clear wood

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Thesis work: October 2019 – September 2022

Context and objectives

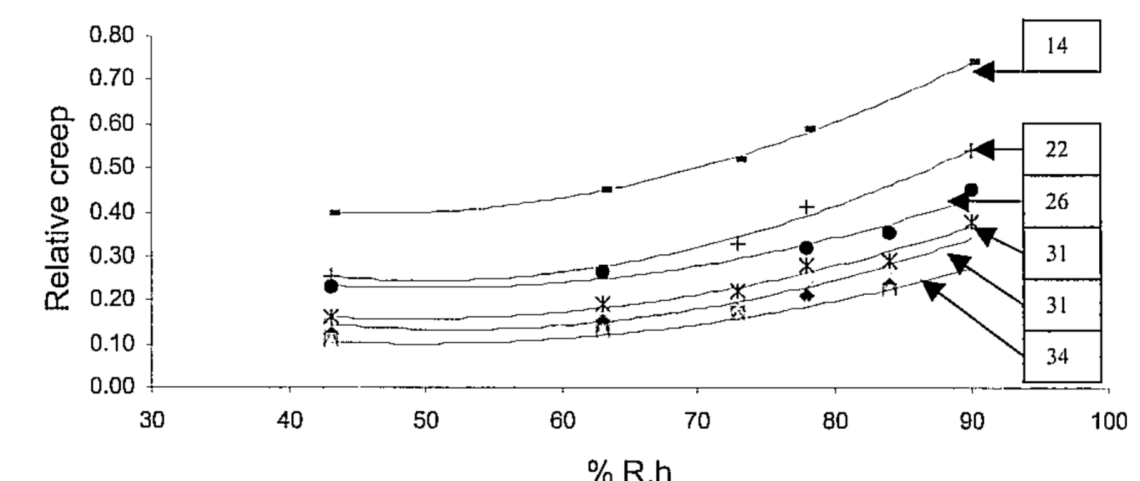


Fig. 1: Evolution of relative creep after 1 week at various relative humidity levels and for different values of specific modulus (GPa) indicated on each curve (Matar 2003)

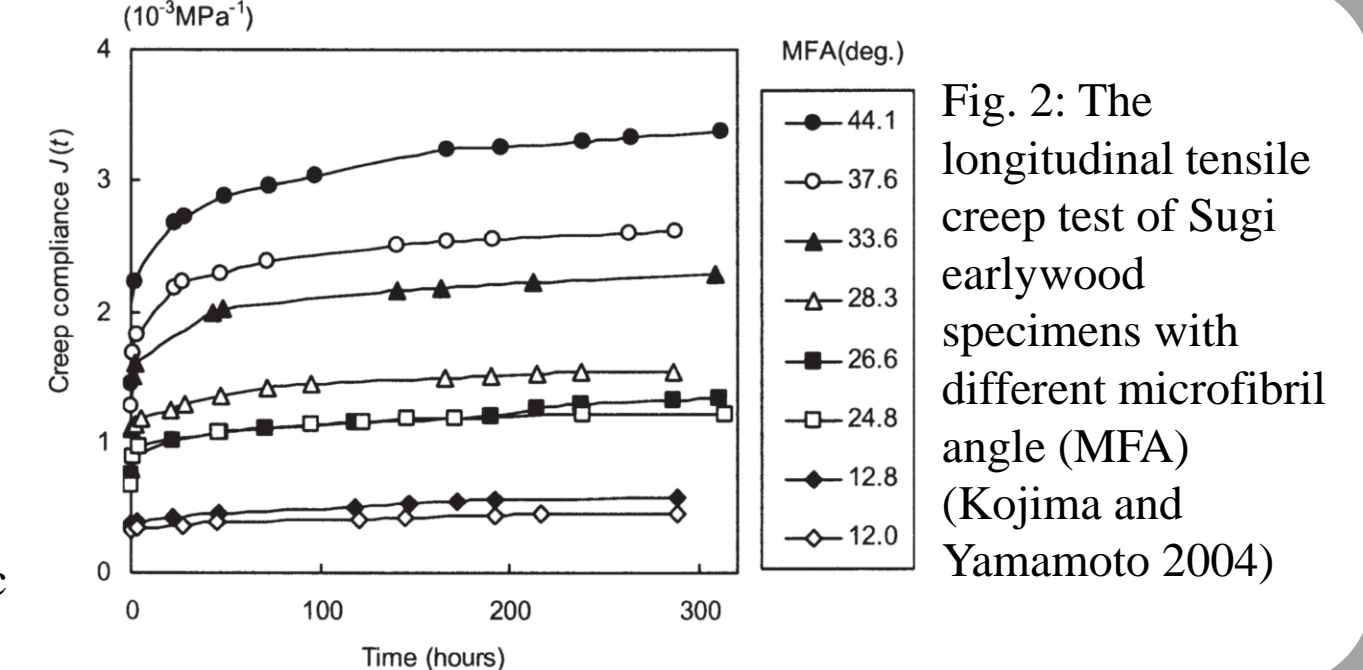


Fig. 2: The longitudinal tensile creep test of Sugi earlywood specimens with different microfibril angle (MFA) (Kojima and Yamamoto 2004)

Materials and Methods

Experimental process

- Wood materials: Douglas fir, Poplar, European Beech, European Oak
- Small clear wood specimens with the size 150 mm (L) * 12 mm (b) * 2 mm (h)
- All the specimens were scanned at room condition and average grain angle was measured by ImageJ from the photos (Fig.3 c).
- The specimens were stabilized in climatic chamber at 20 °C and relative humidity (RH) 85% then density (ρ) and specific modulus (E_s) were measured (Tab.1).
- 29 Douglas fir samples, 34 Poplar samples, 33 Beech samples, and 12 Oak samples (108 samples in sum) were chosen in sampling and conducted creep test.
- 7-day 4-point bending test (Fig.3 a b) with average loading stress 10.52 (± 3.05) MPa was conducted in climatic chamber at 20 °C and RH=85%.
- Data was collected through strain gauges (KYOWA KFGS-5-120-C1-11) on both sides of the specimen and connected to the TDS-120 data logger.

Tab. 1 : The average of the physical and mechanical properties of the specimens

	Number	ρ (g/cm ³)*	E_s (MPa)*	Grain _{avg} (°)
Douglas fir (Pseudotsuga menziesii)	119	0.54 (± 0.03)	19.73 (± 4.15)	2.1 (± 0.9)
Poplar (Populus spp.)	105	0.45 (± 0.02)	19.56 (± 1.61)	3.5 (± 2.7)
European Beech (Fagus sylvatica)	109	0.73 (± 0.02)	17.82 (± 2.21)	2.1 (± 0.8)
European Oak (Quercus petraea)	49	0.63 (± 0.02)	13.61 (± 2.18)	2.7 (± 1.2)

* measured at 20 °C and RH = 85%

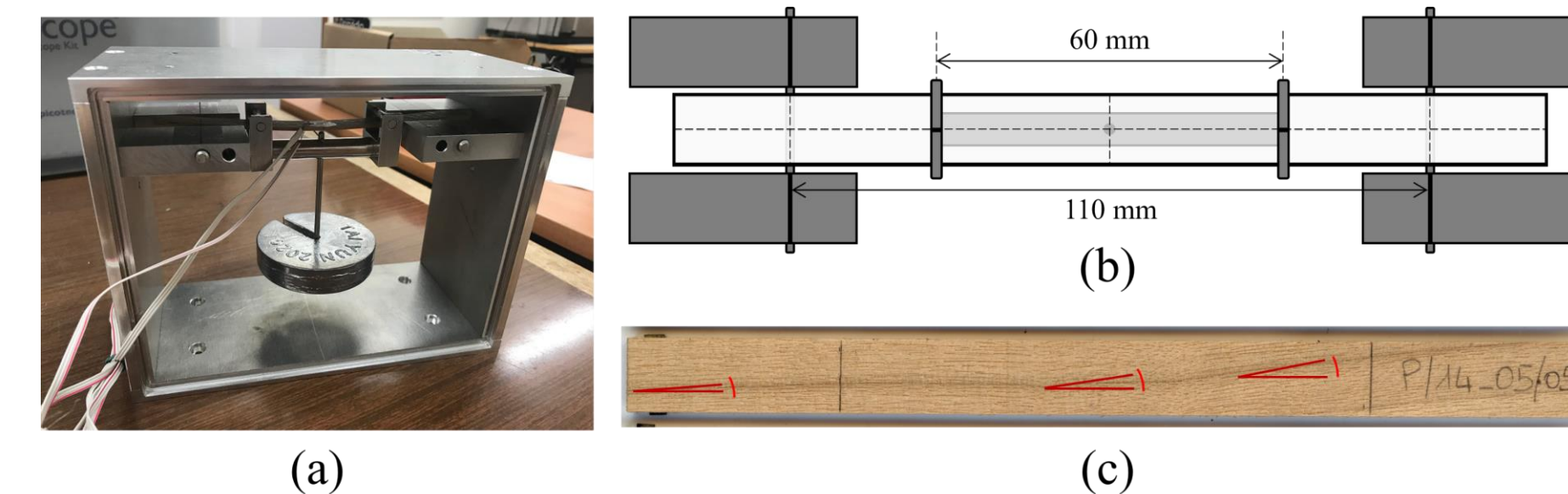


Fig 3: (a) 4-point bending test system for small clear wood. (b) Dimension of the loading system. (c) Measuring method of grain angle.

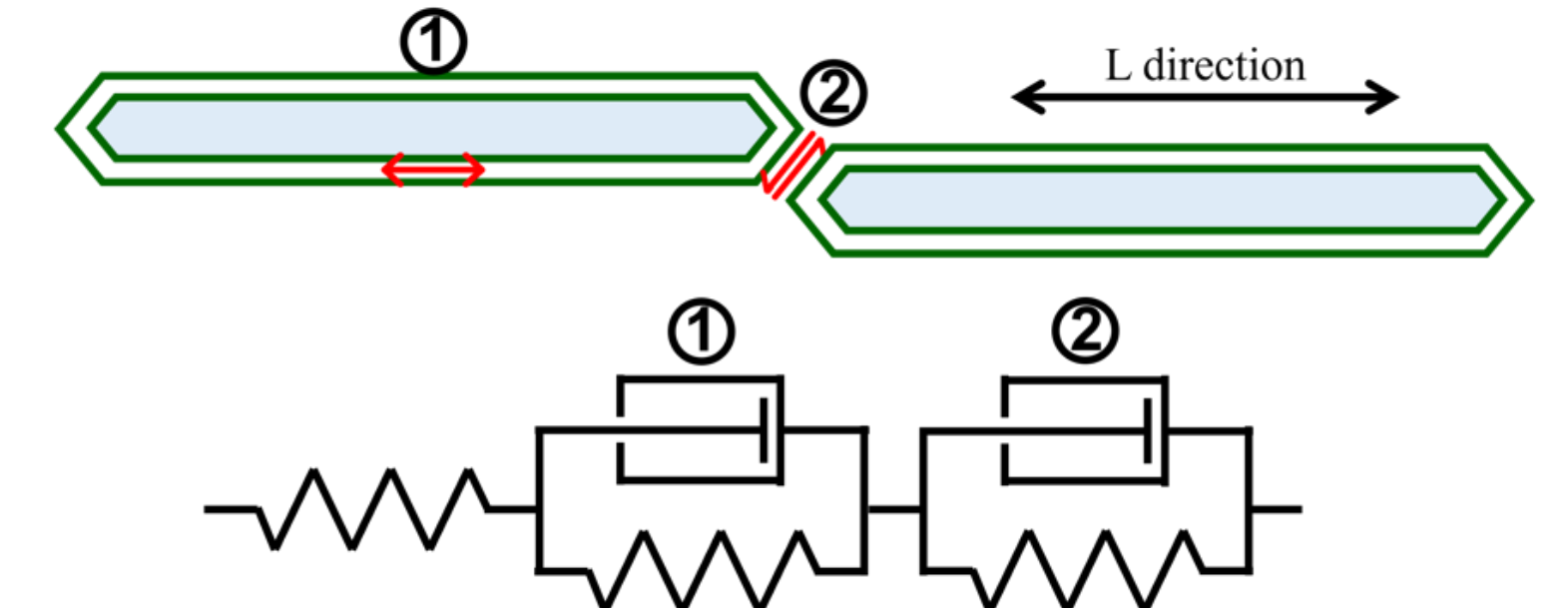


Fig. 4 : Assumptions of creep behavior in the cell scale: deformation of the cell wall (1) and sliding between cells (2), proposition of a model to represent both phenomena.

Assuming that the creep behavior happens at the cellular level,

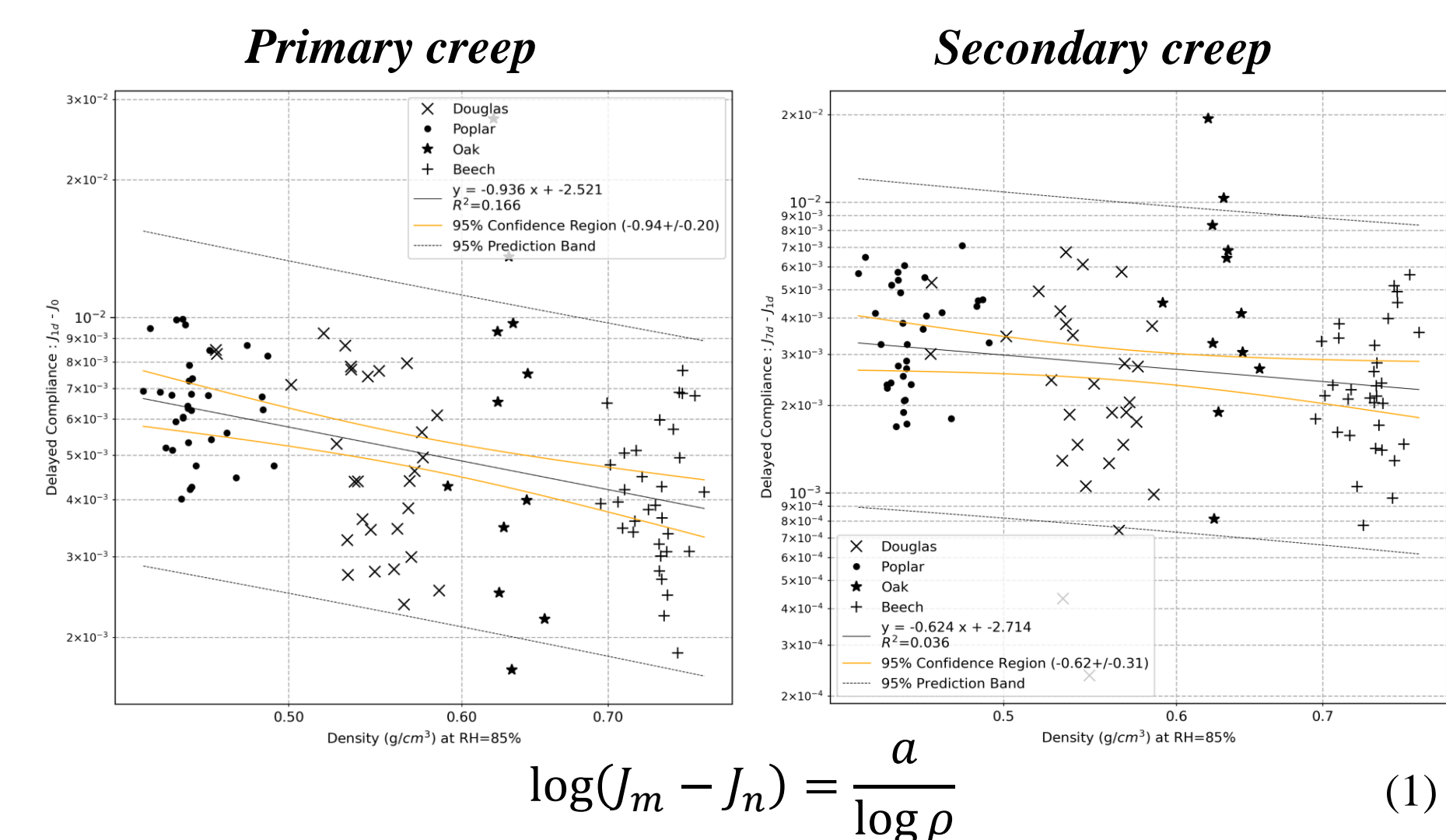
The **two** main hypothesis in this study:

- ① Delayed deformation is caused by the increased deformation of the cell wall.
 - Reorganization of microfibrils.
 - Deformation of the amorphous regions in cell wall;
- ② Creep deformation due to the sliding between the cells

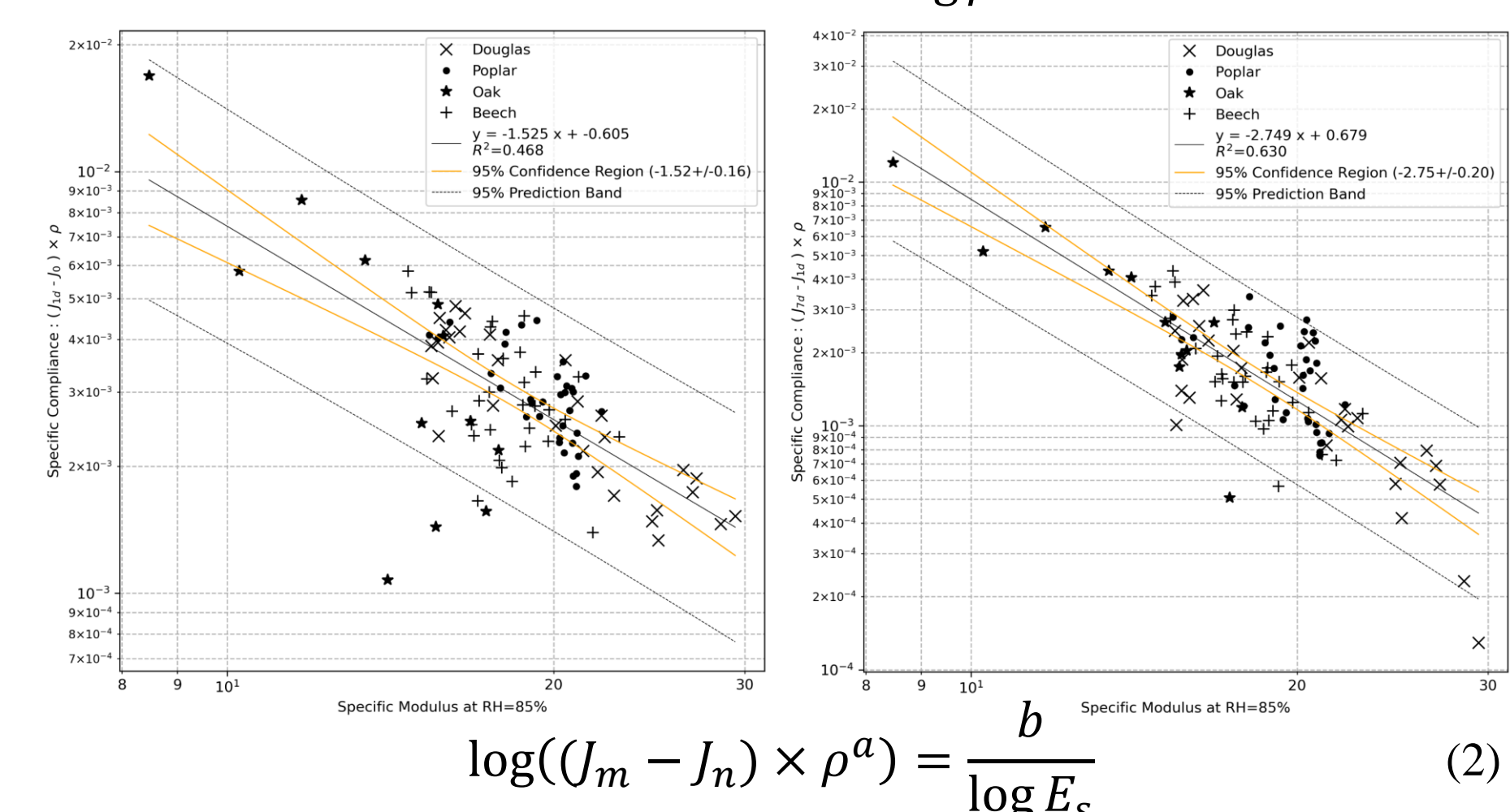
Linear model

The delayed compliance:

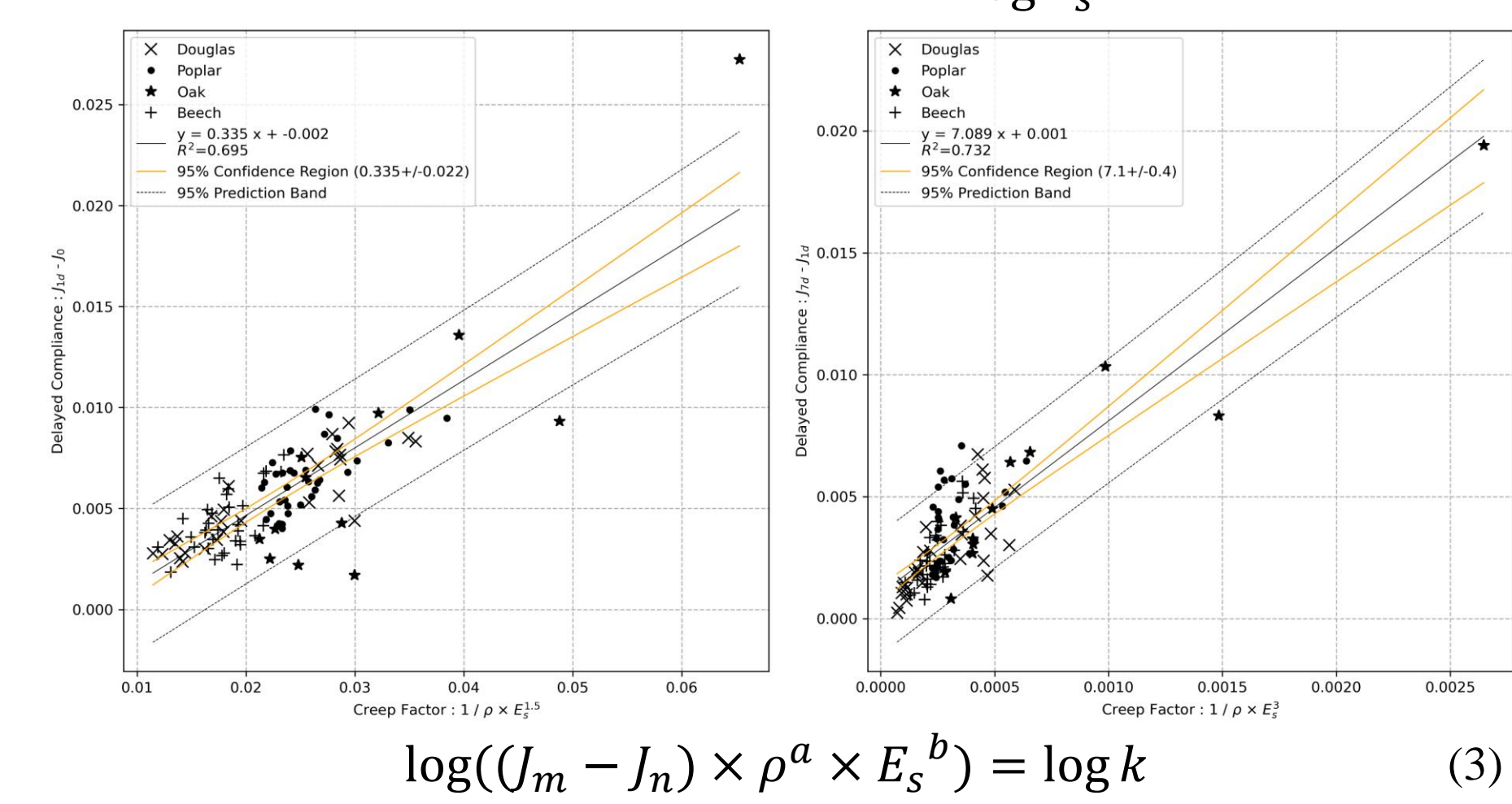
- primary creep: $J_{1d} - J_0$
 - Secondary creep: $J_{7d} - J_{1d}$
1. Density is negatively proportional to delayed compliance
→ Creep behavior occurring on the cell wall.
 2. Specific compliance = delayed compliance x density
→ Eliminates the effect of density.
 3. The specific compliance has a strong linear relationship with the specific modulus and is more strongly correlated in secondary creep than in primary creep.



$$\log(J_m - J_n) = \frac{a}{\log \rho} \quad (1)$$



$$\log(J_m - J_n) \times \rho^a = \frac{b}{\log E_s} \quad (2)$$



$$\log((J_m - J_n) \times \rho^a \times E_s^b) = \log k \quad (3)$$

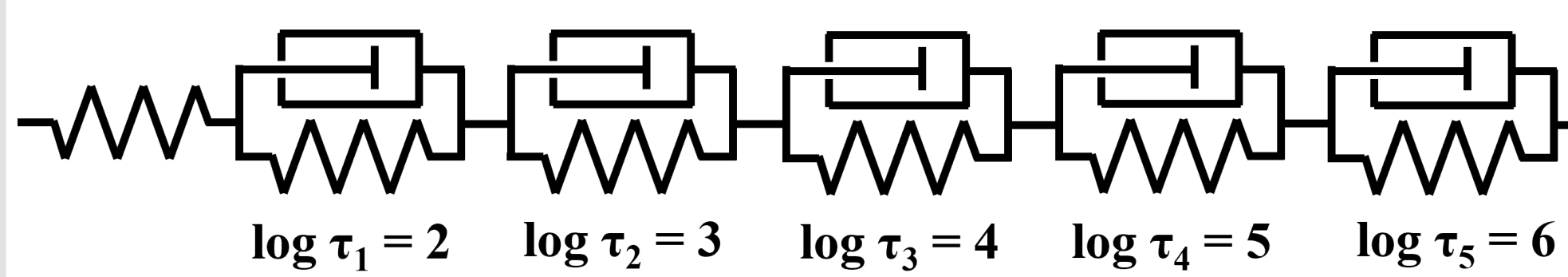
Discrete compliance model

From linear model result:

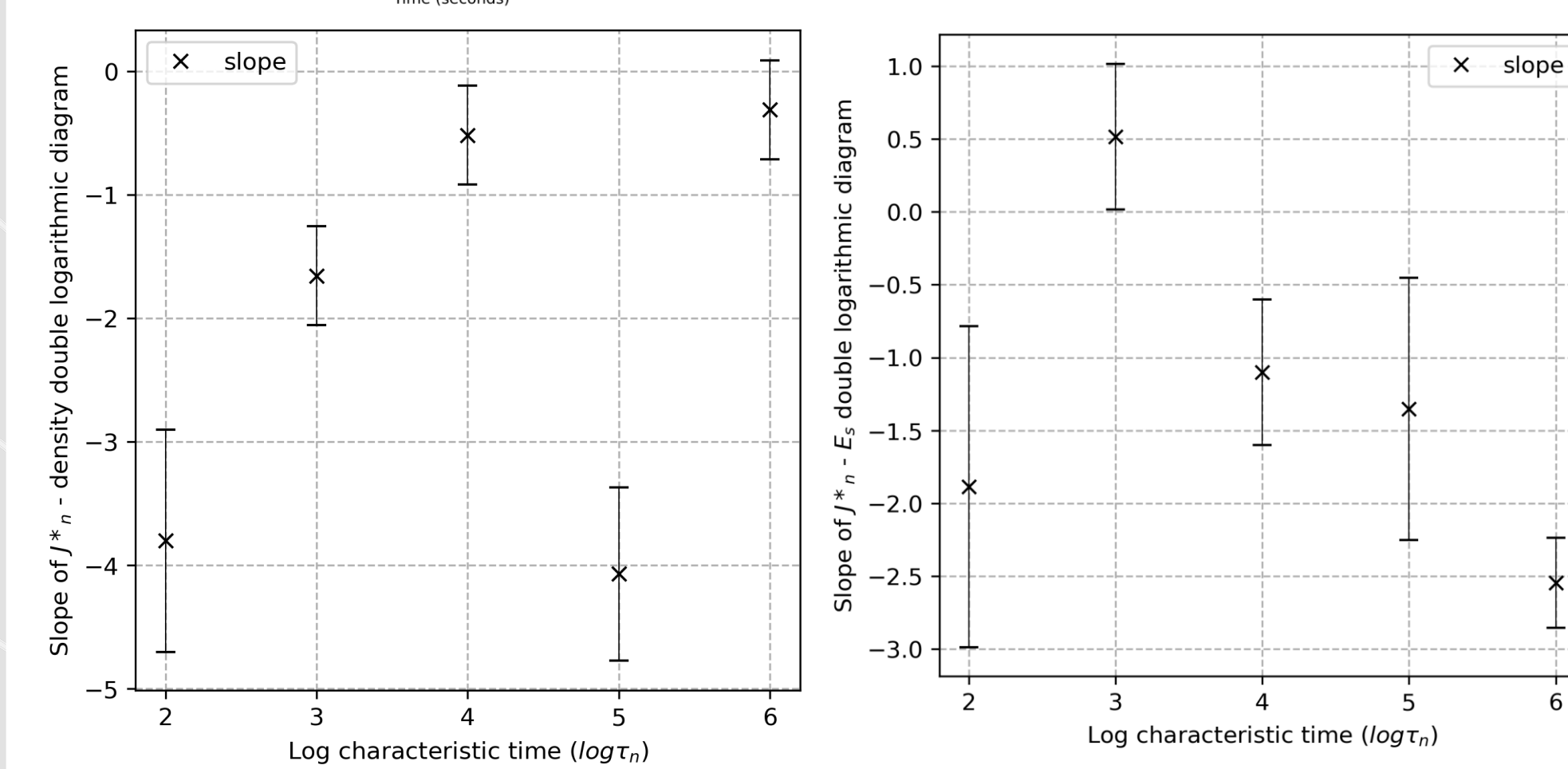
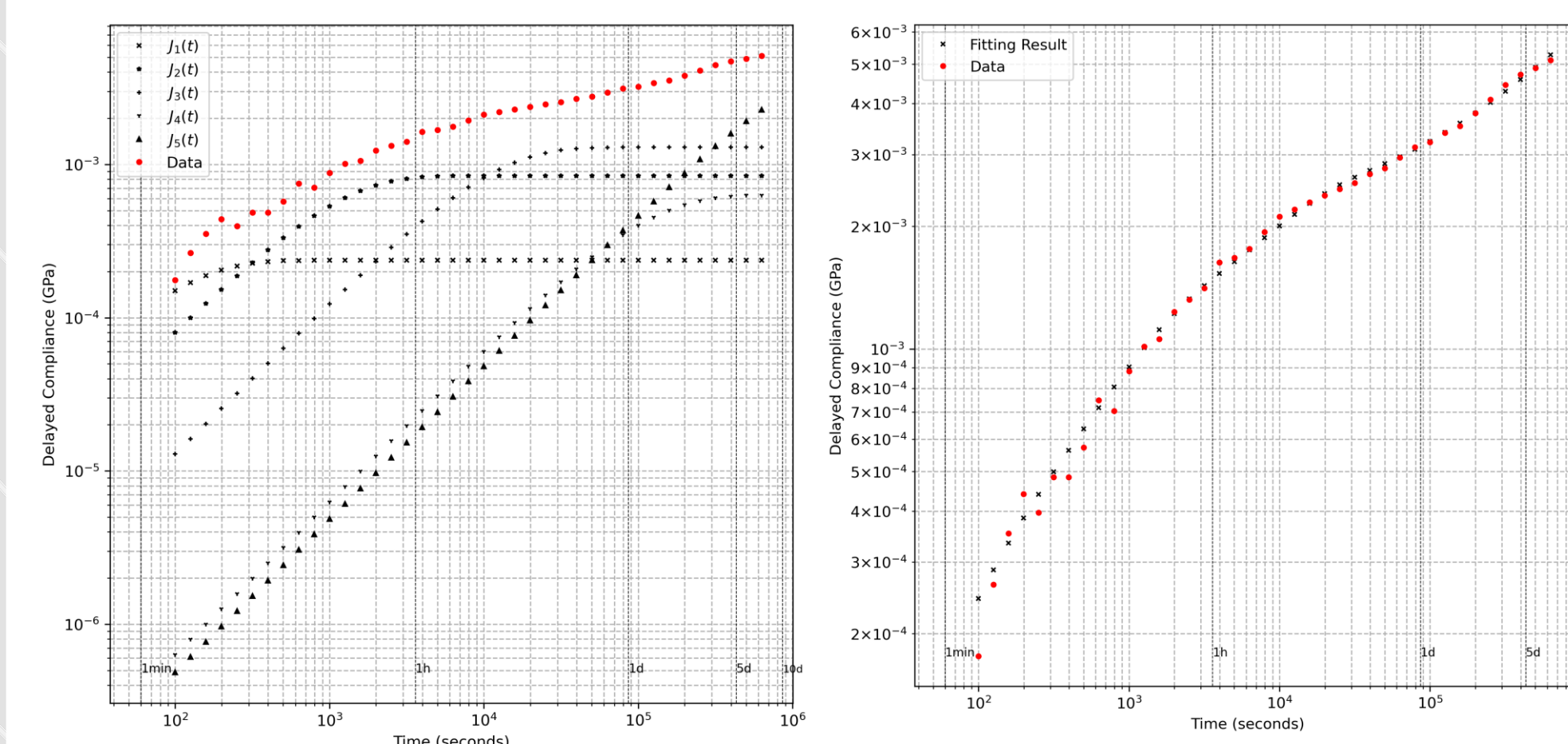
- The predictors have different effects on primary and secondary creep.
- The effect of predictors change with time.

To understand the relationship between time and predictors, the discrete compliance model assumes that the entire creep model is constructed from 5 kelvin bodies. The whole creep process is divided into 5 parts by characteristic time, and J^*n is the fitted parameter for each creep data. Through the regression slope of J^*n and predictors, we can obtain trends in the degree of impact.

n	1	2	3	4	5
characteristic time (τ) (seconds)	100	1000	1000	10000	100000
$\log \tau_n$	2	3	4	5	6



$$J(t) = J_0 + \sum_{n=1}^5 J^*n(t) = J_0 + \sum_{n=1}^5 J^*n (1 - e^{-t/\tau_n})$$



Multiple regression model

From linear model and discrete compliance model:

- The effect of density and specific modulus varies with time.
- It is present on the subdivision of the factor.

1. J^*i is defined as a function of density and specific modulus.
2. Density and specific modulus is defined as polynomial equations of time.
3. 10 parameters ($i_a, s_a, q_a, c_a, i_b, s_b, q_b, i_c, s_c, q_c$) are calculated by test result.
4. $\log \tau_i$ value: from 2 to 5.5 every 0.1

The best-fit parameters are shown in Table 2, and some examples of the fit results are shown below. In the figure of $b(\log \tau_i)$ and $c(\log \tau_i)$, it shows a similar trend to the previous model, which present that the creep behavior start from the deformation of cell wall, then transfer to intercellular sliding.

$$J(t, \rho, E_s) = J_0 + \sum J^*i(t, \rho, E_s) \times (1 - e^{-t/\tau_i}) \quad (4)$$

$$J^*i(t, \rho, E_s) = a(\log \tau_i) \times \left(\frac{\rho}{\rho_0}\right)^{b(\log \tau_i)} \times \left(\frac{E_s}{E_{s0}}\right)^{c(\log \tau_i)} \quad (5)$$

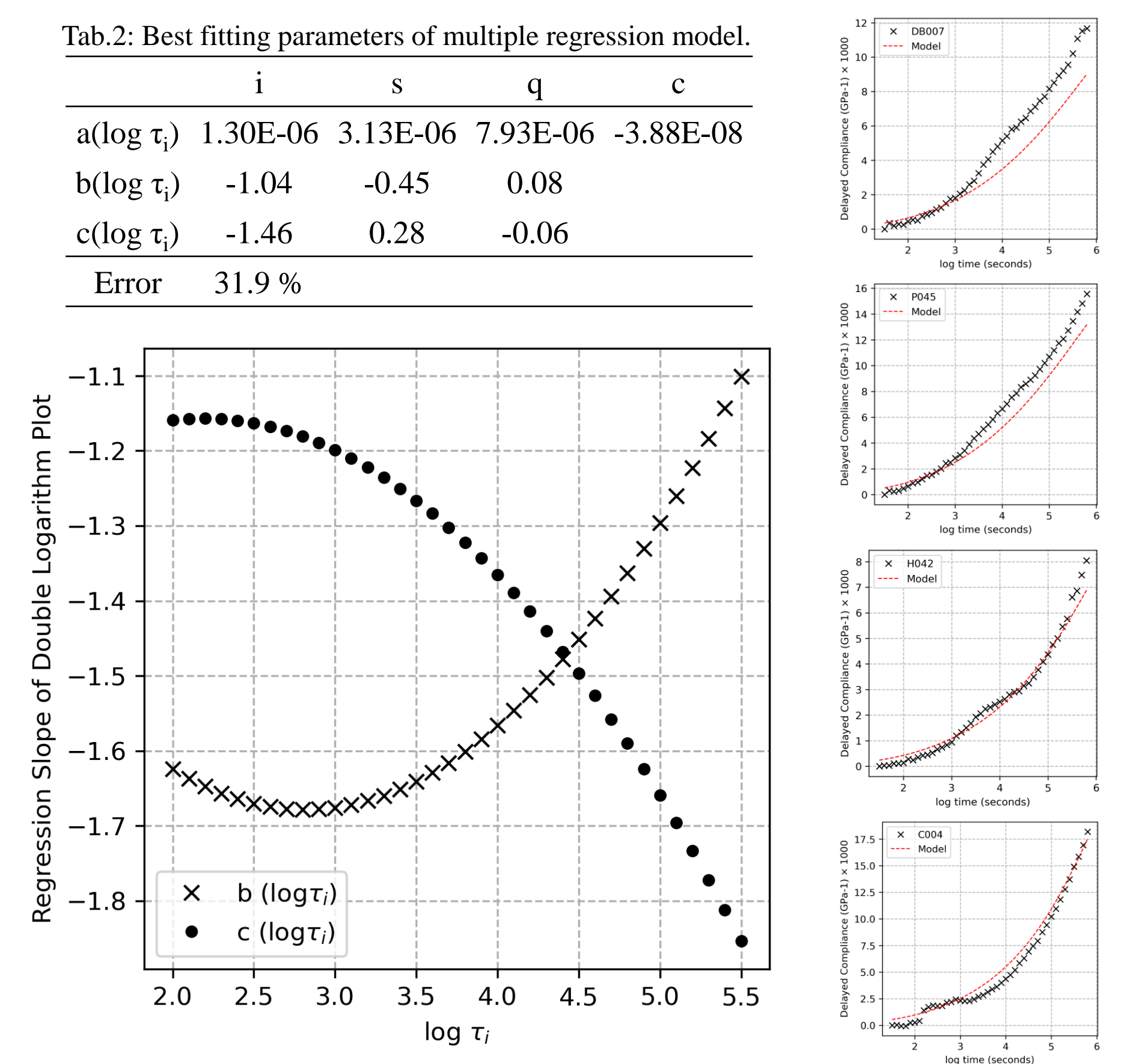
$$a(\log \tau_i) = i_a + s_a \times \log \tau_i + q_a \times (\log \tau_i)^2 + c_a \times (\log \tau_i)^3 \quad (6)$$

$$b(\log \tau_i) = i_b + s_b \times \log \tau_i + q_b \times (\log \tau_i)^2 \quad (7)$$

$$c(\log \tau_i) = i_c + s_c \times \log \tau_i + q_c \times (\log \tau_i)^2 \quad (8)$$

Tab.2: Best fitting parameters of multiple regression model.

	i	s	q	c
$a(\log \tau_i)$	1.30E-06	3.13E-06	7.93E-06	-3.88E-08
$b(\log \tau_i)$	-1.04	-0.45	0.08	
$c(\log \tau_i)$	-1.46	0.28	-0.06	
Error	31.9 %			



Conclusion

In this study, the use of small clear wood was able to control the macroscopic material properties and reduce its variability. Density corresponds to material properties larger than cellular scale, and specific modulus corresponds to the property of the material that is smaller than the cellular scale, which is the microfibril angle or the grain angle. The assumption of the model in this study is that if delayed compliance is proportional to density, then creep behavior occurs only at the cell wall. It is proved in the linear model. However, we also observed that the magnitude of the effect of these factors on creep behaviors changed over time. Through the discrete compliance model, we found the compliance parameter values at characteristic time and the trend is nonlinear. Therefore, in the multiple regression model, we assume that the relationship between creep parameters and time is a polynomial function, which shows the degree of influence of material properties on the creep behavior change with time. The fitting results show that the effect of density decreases with time, while the effect of specific modulus increases. From this, we can infer that the creep behavior of wood starts with the deformation of the cell walls and then shifts to the intercellular space, which is related to the MFA and the grain angle and is presented by the specific modulus.

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Acknowledgments

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