Explanation of Thermo-Hydraulic-Mechanical Behavior of Geomaterials in So-Called Isothermal Heating Test

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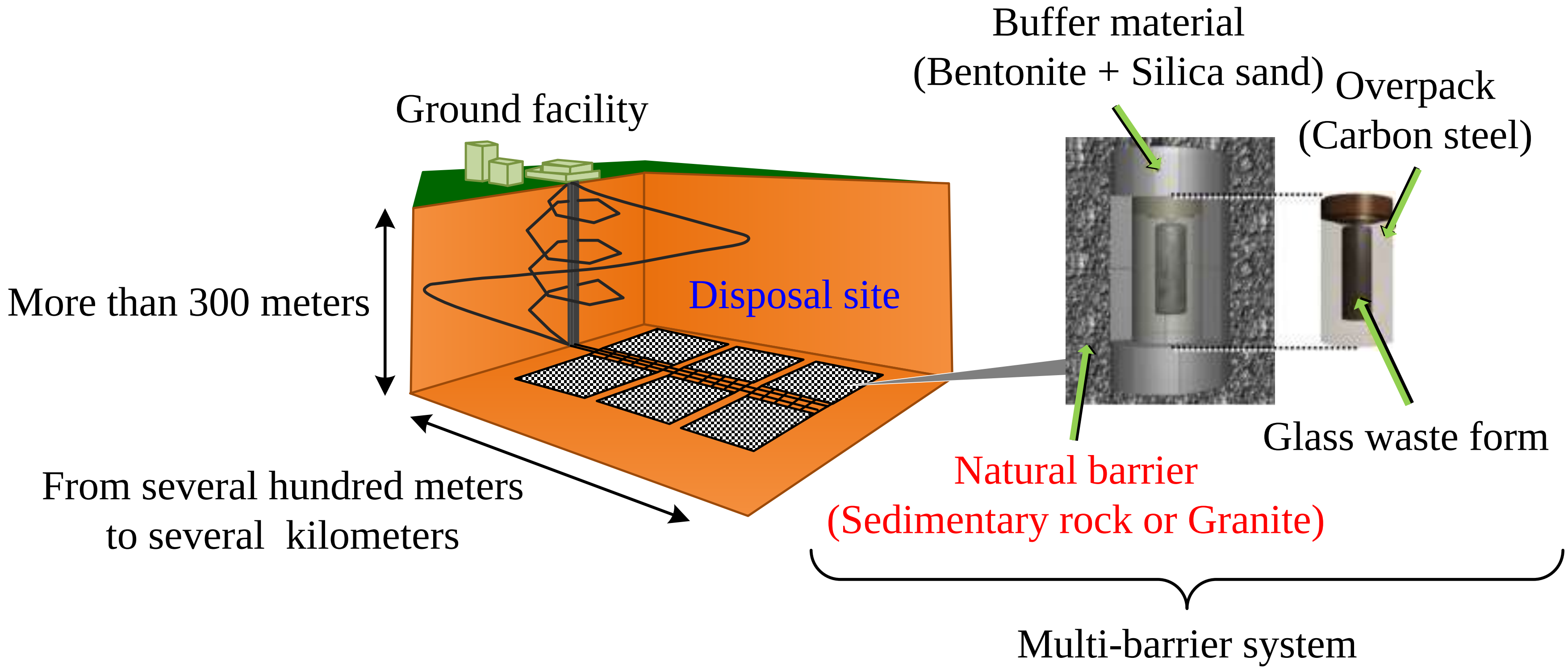
14-17 December, 2016, CSRME 14th Biennial National Congress

Background ~high-level radioactive waste~

- In considering the problem of the deep geologic disposal for high level radioactive waste, thermo-hydraulic-mechanical (THM) behavior of artificial barrier, mainly composed of highly compacted bentonite and very stiff clays, is a very important factor that needs to be studied.
- Many laboratory, field tests and numerical analyses including constitutive modelling related to thermodynamic behaviors of geomaterials have been done.



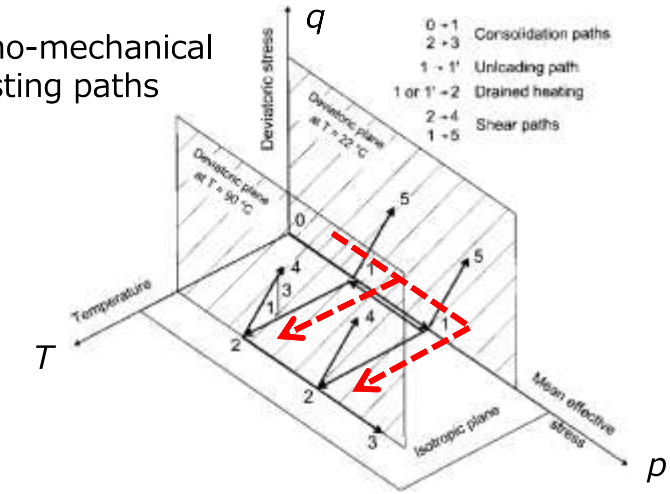
Japan Nuclear Cycle Development Institute (1999): JNC TN1400 99-020

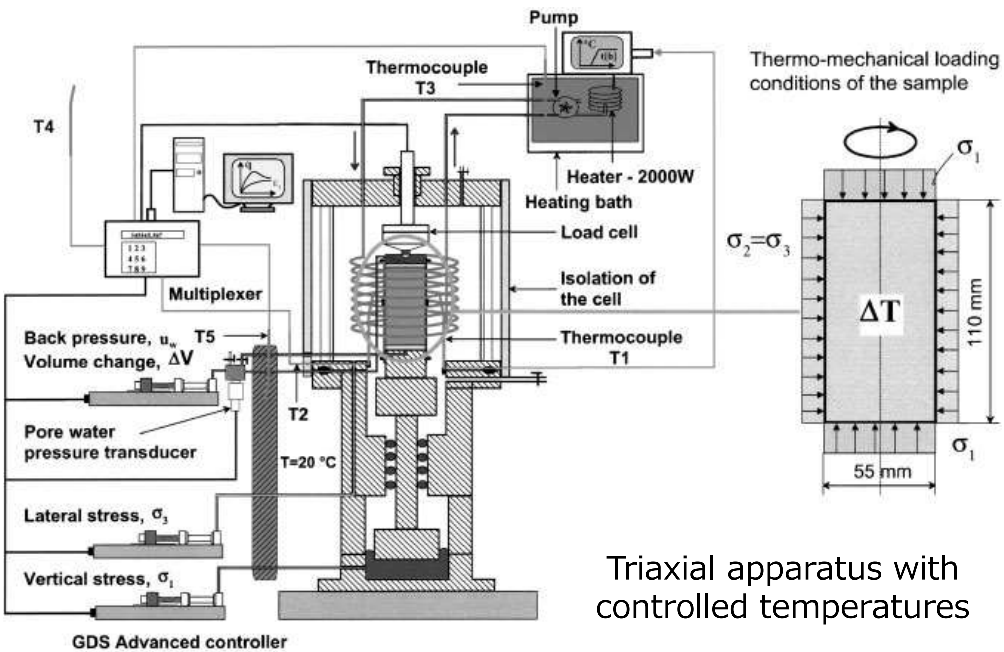
Previous studies ~Cekerevac and Laloui (2004)~

Heating test

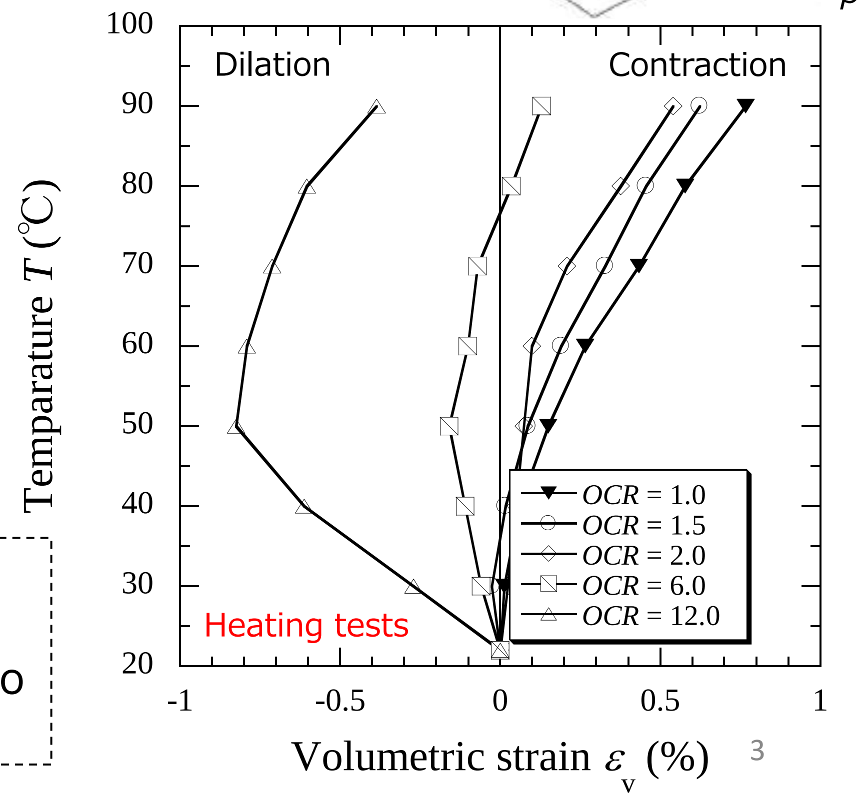
- The specimen was heated gradually up to 90°C with a rate of about 1℃/hour (Initial temperature: 22°C)

Thermo-mechanical testing paths





Triaxial apparatus with controlled temperatures



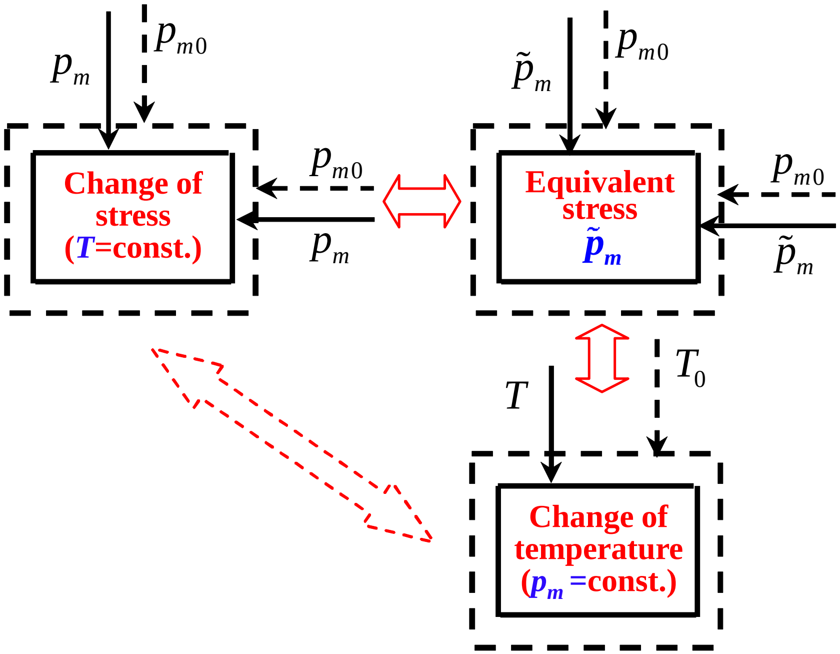
- ➢ The heat-induced volumetric strain is dependent on OCR of the soil samples.
- ➢ The specimen will change from contraction to expansion as OCR increases.

等価応力の概念

- 温度変化により，応力変化と弾塑性ひずみが生じる（一定応力条件下）

温度変化による弾性ひずみをフックの法則に基づき，等価応力 $\tilde{p}_m$ を次式で定義

$$\begin{aligned}\tilde{p}_{\mathrm{m}} &= p_{\mathrm{m}} + K\varepsilon_{\mathrm{v}}^{\mathrm{eT}} \\ &= p_{\mathrm{m}} + 3K\alpha^{\mathrm{s}}\varepsilon_{\mathrm{v}}^{\mathrm{eT}}\left(T - T_0\right)\end{aligned} \quad \leftarrow \quad \varepsilon_{\mathrm{v}}^{\mathrm{eT}} = 3\alpha^{\mathrm{s}}\left(T - T_0\right)$$



～等価応力の概念～
Zhang, S. and Zhang, F. (2009)

p_{m}：実応力
K：体積弾性係数
α^{s}：熱線膨張係数（-）
T：現在の温度
T_0：基準の温度（288K）

Material and physical parameters

FEM Program: "SOFT" (Xiong, Y., 2015)

- THM coupling finite element-finite difference (FE-FD) analysis

Constitutive model: "Modified thermo-elasto-visocoplastic model" (Zhang, S. and Zhang, F., 2009; Xiong, Y., 2015)

- Subloading (Hashiguchi, K. et al., 1977) & t_{ij} transformed stress space (Nakai, T. and Mihara, Y., 1984)
- Thermal expansion coefficient (a^s_T) → Any material will exhibit expansion whenever it is heated at elementary level

Parameters	Unit	Kaolin clay
Compression index λ	-	0.10
Swelling index κ	-	0.01
Critical state stress ratio R_f	-	2.09
Void ratio N (p = 98 kPa on *N.C.L.*)	-	0.93
Poisson's ratio ν	-	0.35
Parameter for plastic potential shape β	-	1.5
Time dependent parameter α	-	0.0
Time dependent parameter C_n	-	0.0
Degradation parameter of overconsolidation state a	-	2000
Permeability k	m/min	3.0E-9
Thermal expansion coefficient of solid phase α^s_T	K^{-1}	-8.0E-6
Thermal expansion coefficient of fluid phase α^f_T	K^{-1}	-2.07E-4
Specific heat of solid phase c^s	J kg^{-1} K^{-1}	840
Specific heat of fluid phase c^f	J kg^{-1} K^{-1}	4184
Thermal conductivity of solid phase k^s_T	kJ m^{-1} K^{-1} min^{-1}	0.18
Heat transfer coefficient of air boundary α_c	kJ m^{-2} K^{-1} min^{-1}	230

Yield function

$$f\left(t_{ij}, \varepsilon_v^p, T\right) = \ln\left(\frac{t_N}{t_{N0}}\right) + \xi(X) - \frac{1}{C_p}\left(\varepsilon_v^p - \frac{\rho}{1+e_0}\right) = 0$$

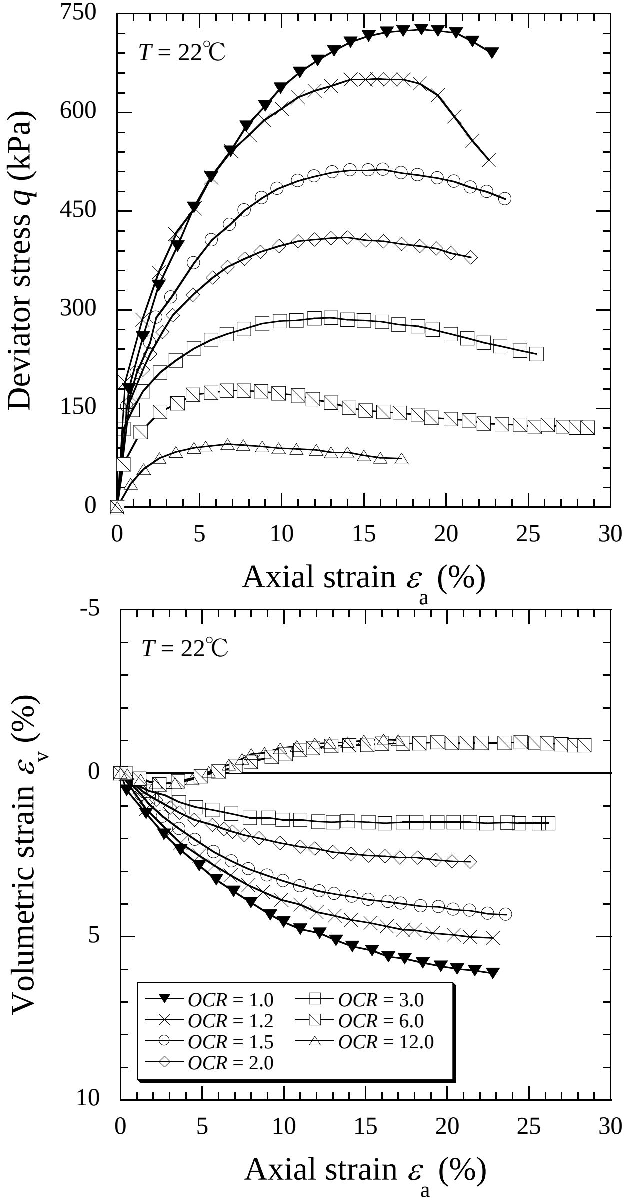
Evolution law

$$\frac{\dot{\rho}}{1+e_0} = -\Lambda \frac{G(\rho, t)}{\tilde{t}_N} + h(t)$$

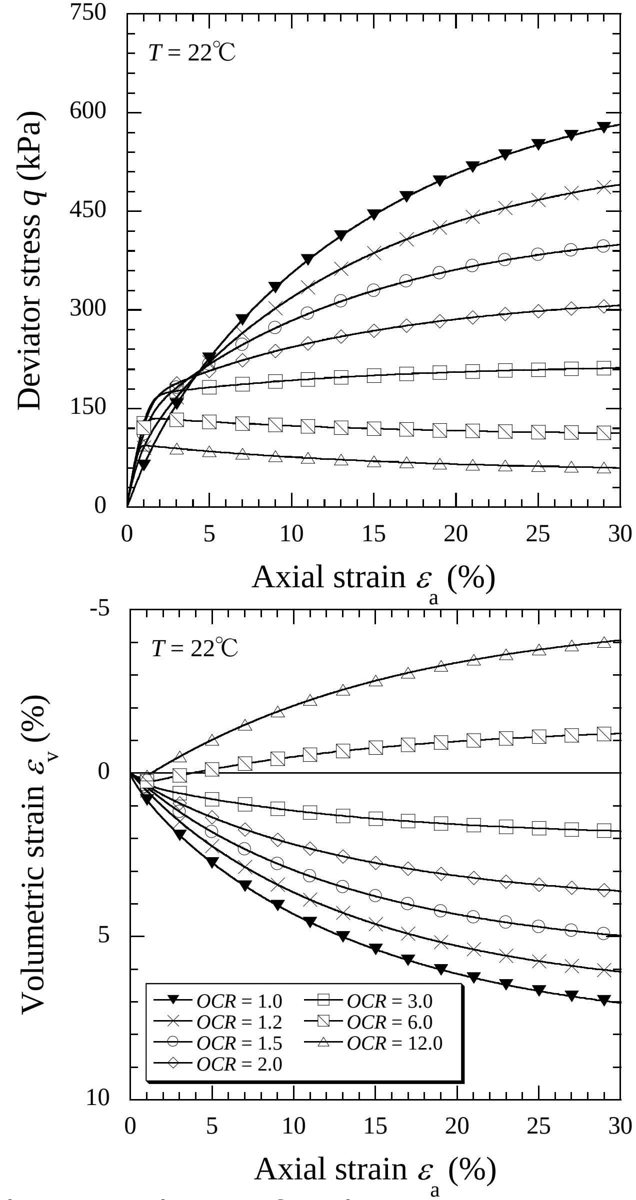
$$= -\Lambda \frac{a \cdot \rho \cdot \rho^{C_n \ln(1+t/t_1)}}{\boxed{t_N + 3K\alpha_T^s (T - T_0)}} + \dot{\varepsilon}_v^0 (1 + t/t_1)^{-\alpha}$$

Element simulation

Observed results



Simulated results

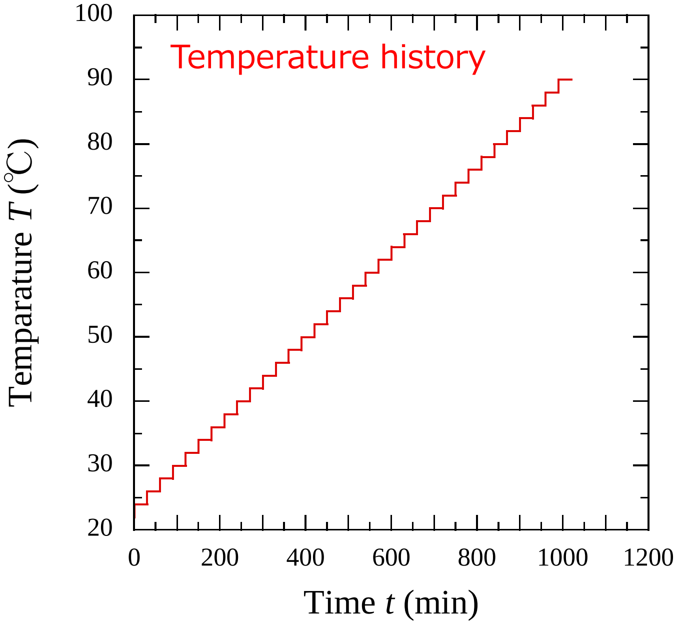


Comparison of observed and simulated stress-strain-dilatancy relations for element tests
(test data: Cekerevac and Laloui, 2004)

Objective and boundary condition

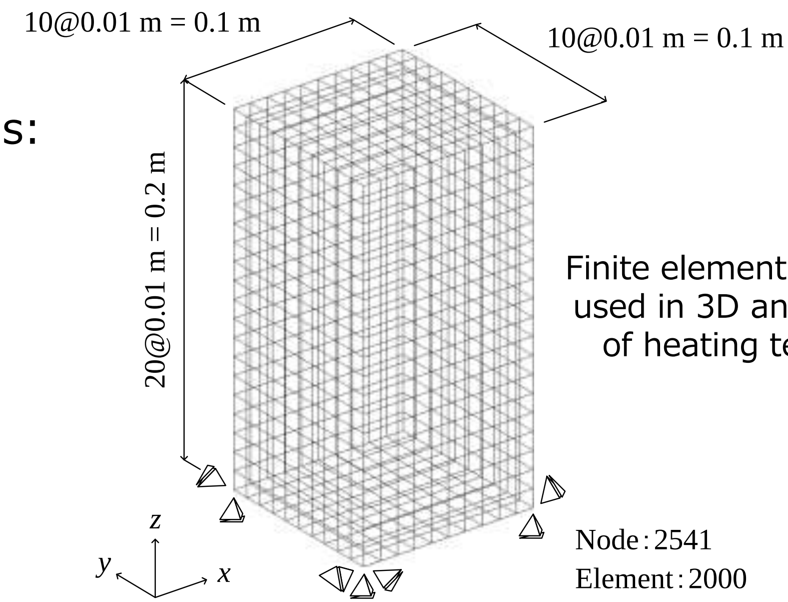
Objective

- Is the contractive behavior of soft clay when heated under constant isotropic stress condition an elementary behavior?
- If not, how to model contractive behavior of soil in the heating test with a rational constitutive model?



Boundary condition

- FEM mesh: Node 2541 and Element 2000
- Hydraulic and thermal boundary conditions: all boundaries are set to be drained and heat source



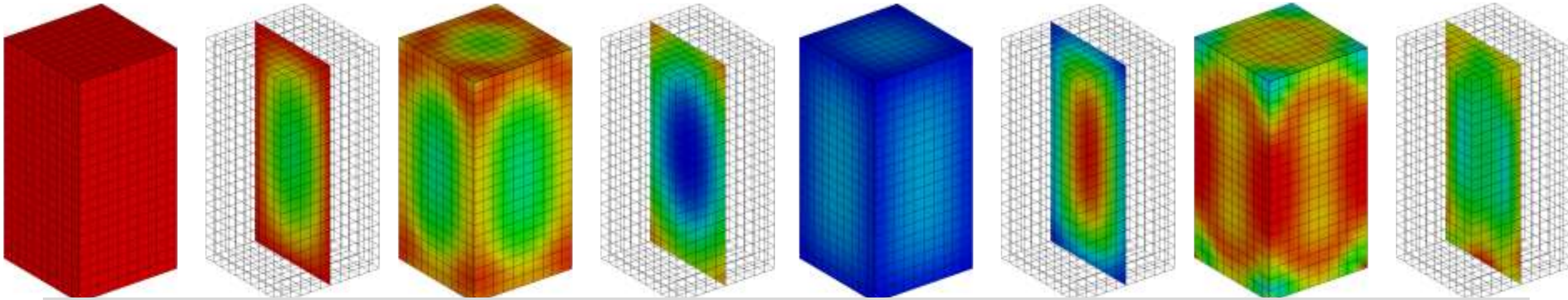
Finite element mesh used in 3D analysis of heating tests

Initial condition

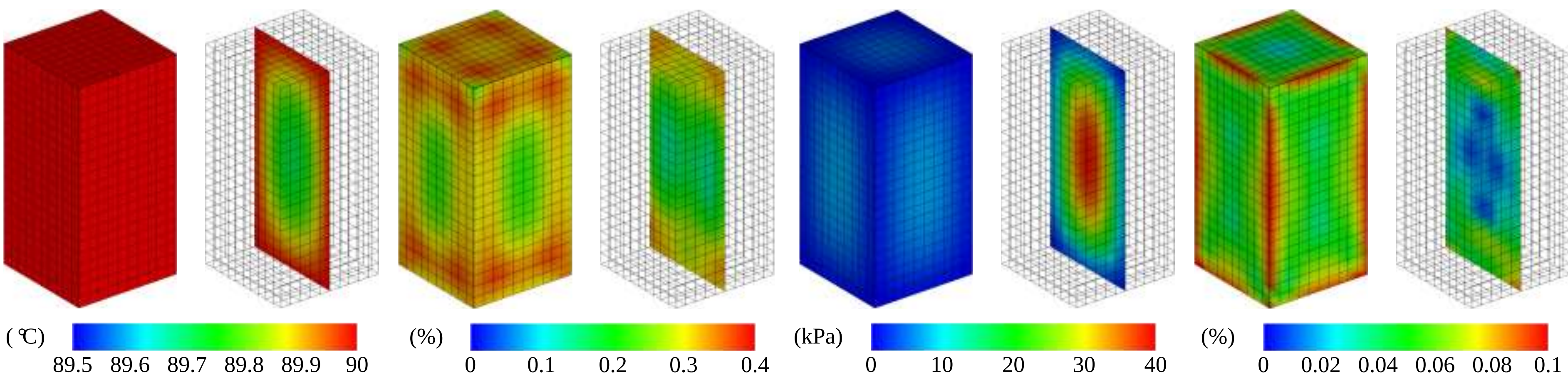
- OCR: 1.0, 1.2, 1.5, 2.0, 3.0, 6.0, 12.0 (Consolidation yield stress=600kPa)
- Temperature: 22℃ (About 4℃/hour)

Heating test (OCR=1.0)

Temperature=26℃



Even if the heating process is very slow, the uneven thermal field within the heating sample may give rise to non-uniform stress and strain fields.

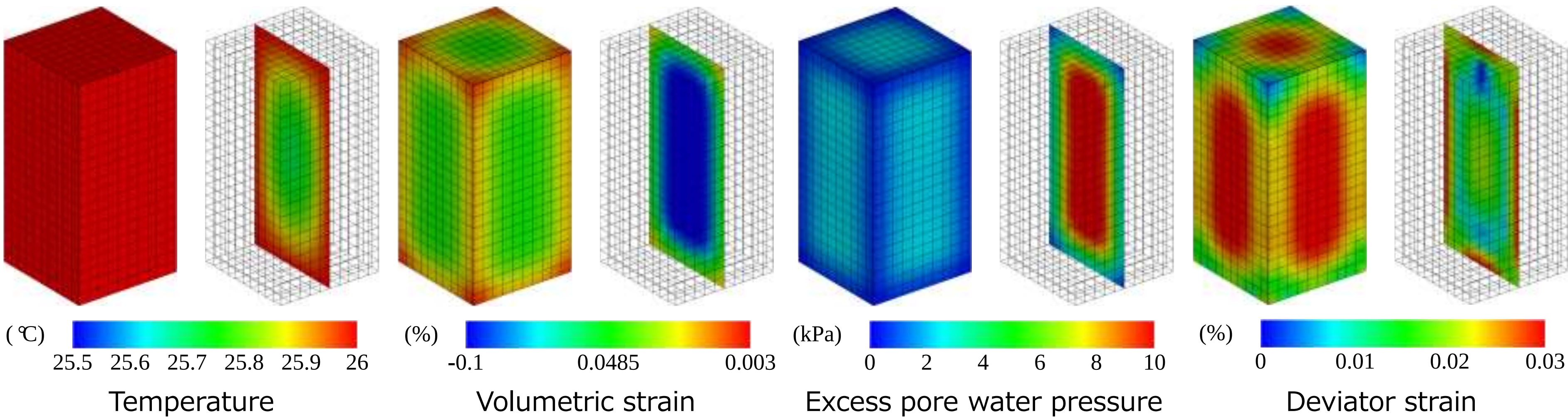


Temperature | Volumetric strain | Excess pore water pressure | Deviator strain

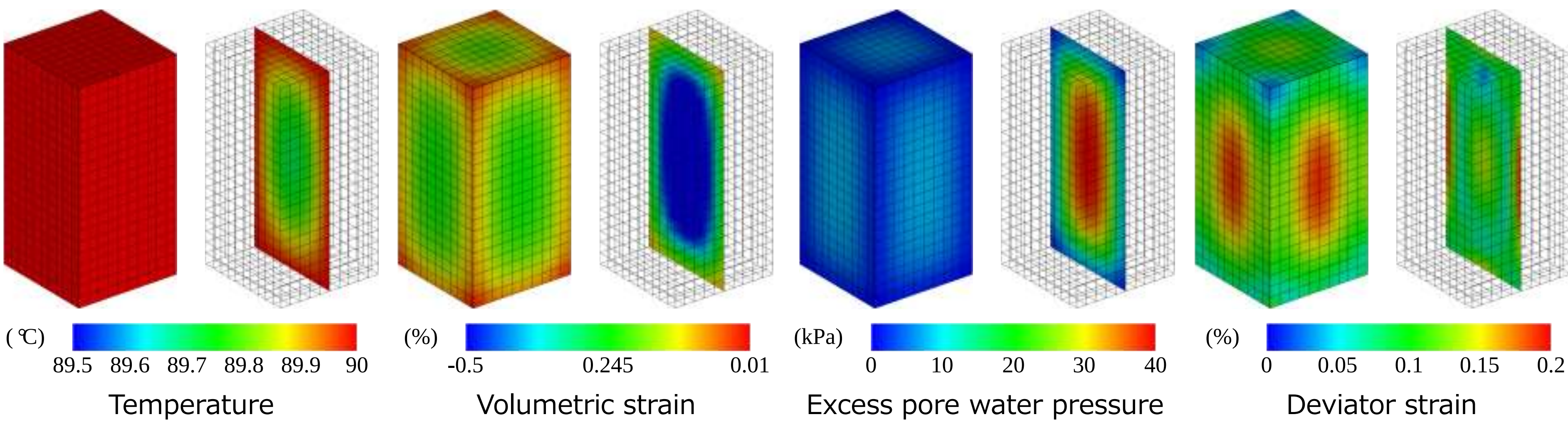
Distributions of various physical quantities within the testing samples (OCR=1.0) at different heating stages

Heating test (OCR=12.0)

Temperature=26℃



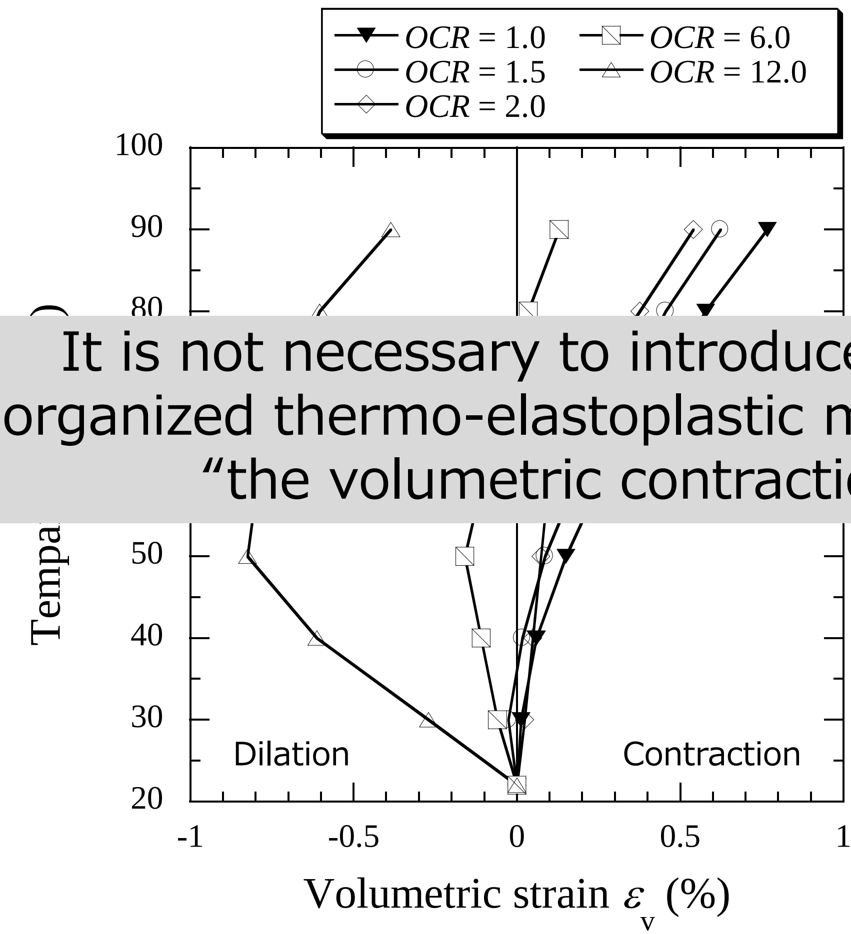
Temperature=90℃



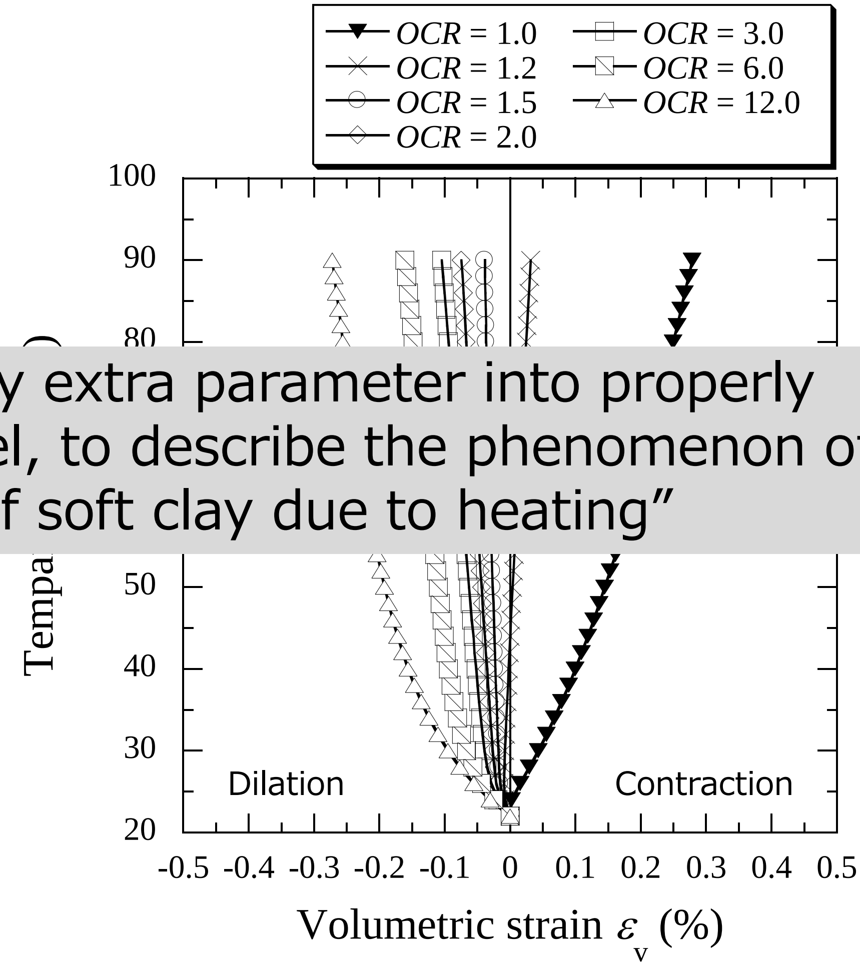
Distributions of various physical quantities within the testing samples (OCR=12.0) at different heating stages

Temperature-volumetric strain relation

Observed results



Simulated results

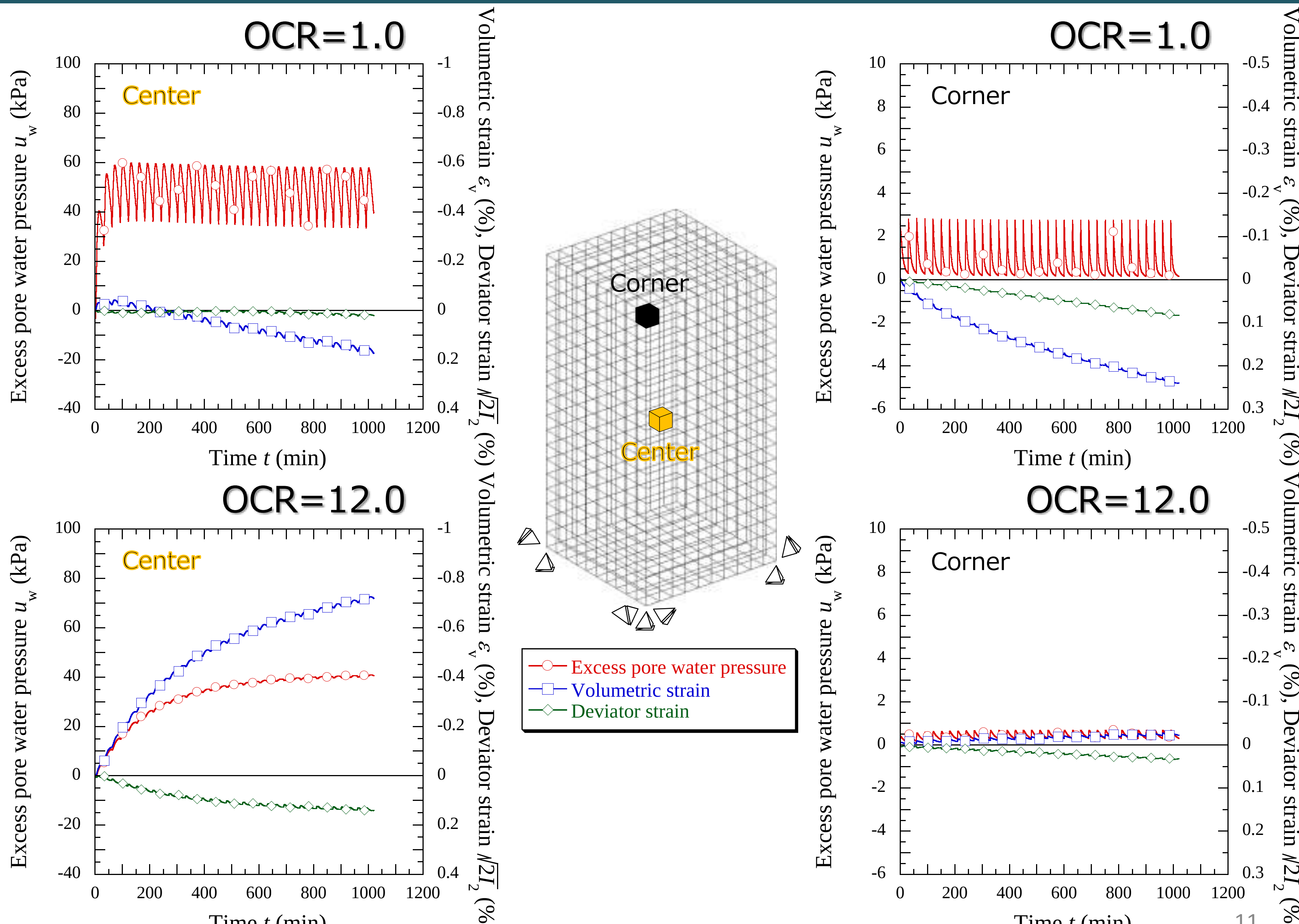


It is not necessary to introduce any extra parameter into properly organized thermo-elastoplastic model, to describe the phenomenon of “the volumetric contraction of soft clay due to heating”

Comparison of observed and simulated temperature-volumetric strain relation (test data: Cekerevac and Laloui, 2004)

- The calculated volumetric strain is on the whole agreed with the testes one in its variation with temperature, though quantitatively there still existed some discrepancy.

Time histories ~u_w, e_v, $\sqrt{2I_2}$~



Time histories of various physical quantities at the center and the corner of the samples with different OCR

The non-uniform stress and strain fields

- The heating process can be roughly divided into two stages:

<u>Stage①: Heat transfer, Stage②: Pore water dissipation</u>

- As the thermal conductivity is much higher than the hydraulic conductivity in soft clay, Stage 1 can be considered as very short compared to Stage 2.
- As the result, thermal dilation is very fast, followed by the water pressure dissipation.
- However, Stage 1 and Stage 2 are not evenly happen within the sample and therefore volumetric change will also become uneven, resulting in contraction in some areas.
- This unevenness will not disappear even if EPWP dissipated completely and the temperature in the whole sample became uniform after long time.
- Because whenever a contractive strain occurs, plastic volumetric strain will also occur and basically it is uneven distributed.

Thanks for listening!