Effects of Stress Rate on Uniaxial Compressive Strength of Rock Salt under 0-100°C

S. Sartkaew
K. Fuenkajorn

Geomechanics Research Unit
Institute of Engineering
Suranaree University of Technology, Thailand

The 11th International Conference on Mining, Materials and Petroleum Engineering
The 7th International Conference on Earth Resources Technology
ASEAN Forum on Clean Coal Technology
November 11-13, 2013, Chiang Mai

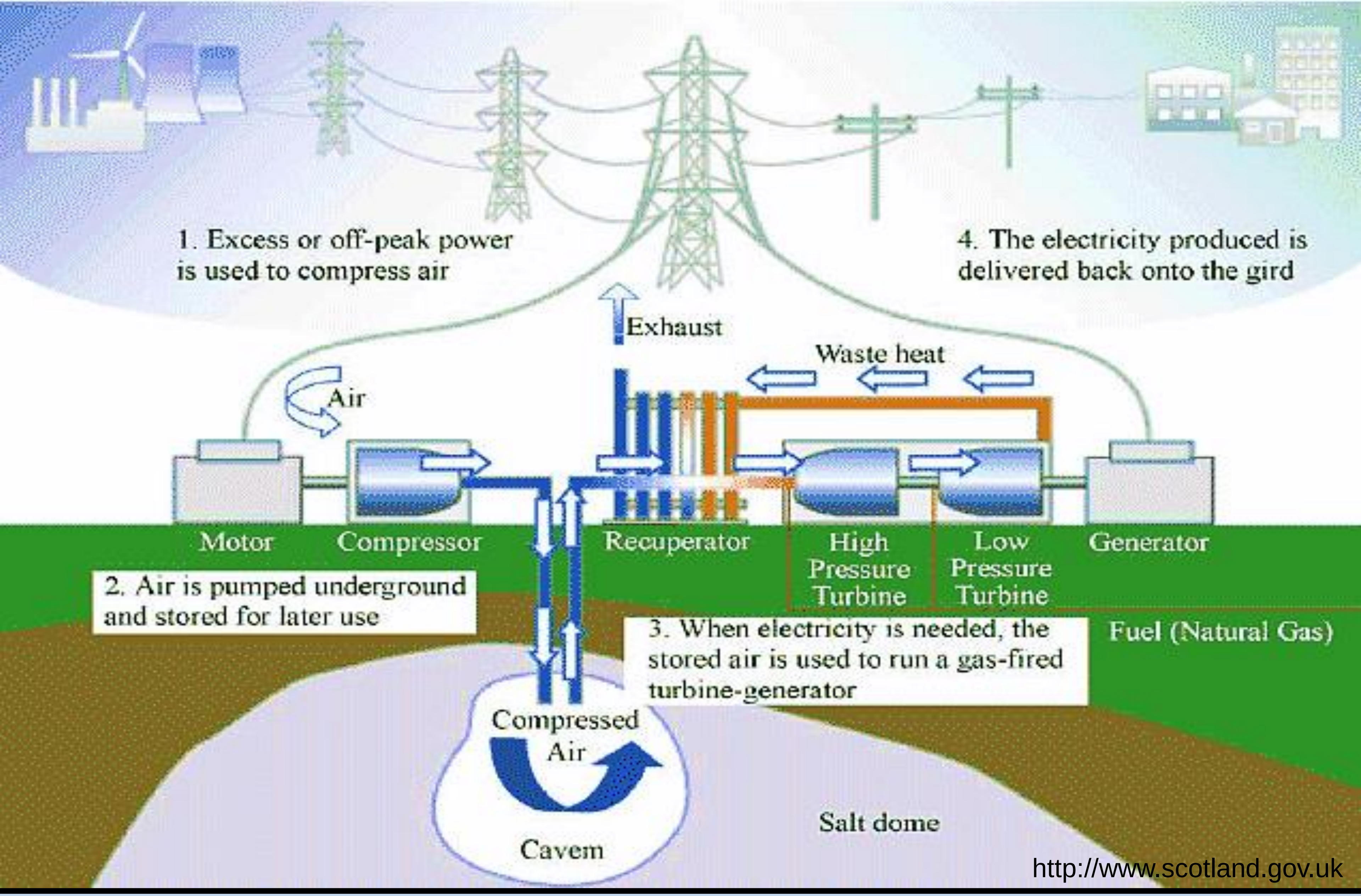
Outline

- ❑ Background and Rationale
- ❑ Objectives
- ❑ Rock Salt Specimens
- ❑ Laboratory Testing
- ❑ Test Results
- ❑ Strength Criterion
- ❑ Discussions and Conclusions

Background and Rationale

www.thailand-map.net

Background and Rationale



1. Excess or off-peak power is used to compress air

2. Air is pumped underground and stored for later use

3. When electricity is needed, the stored air is used to run a gas-fired turbine-generator

4. The electricity produced is delivered back onto the gird

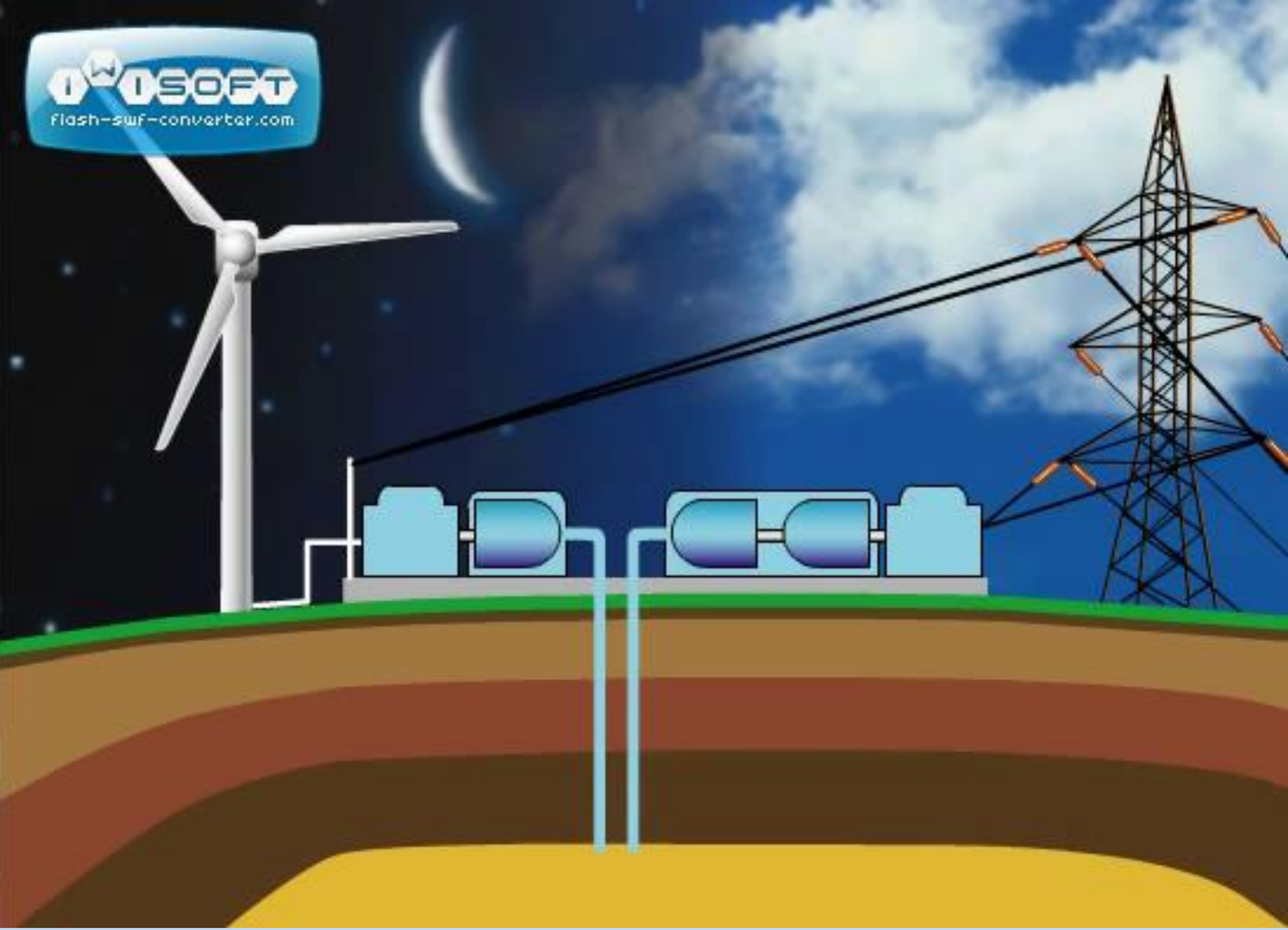
http://www.scotland.gov.uk

Compressed air energy storage power plant (CAES)

Huntorf, Germany (1978)

MacIntosh, U.S.A (1991)

http://www.bine.info



- ☐ The loading rate affects on the compressive strength and deformability of intact rocks (Kumar, 1968; Jaeger *et al*., 2007; Cristescu and Hunsche, 1998; Albertin *et al*., 1999).
- ☐ The strength of salt increases with applied stress and strain rate (Fuenkajorn *et al*., 2012; Liang *et al*., 2011; Hamami, 1999 and Lajtai *et al*., 1991).
- ☐ The rock strength and elastic properties decrease as temperature increase. (Sriapai *et al*., 2012).

Objectives

- ❑ Determine the effect of loading rate and temperature on the compressive strength and deformability of rock salt

- ❑ Derive strength criterion as affected by loading rate and temperature

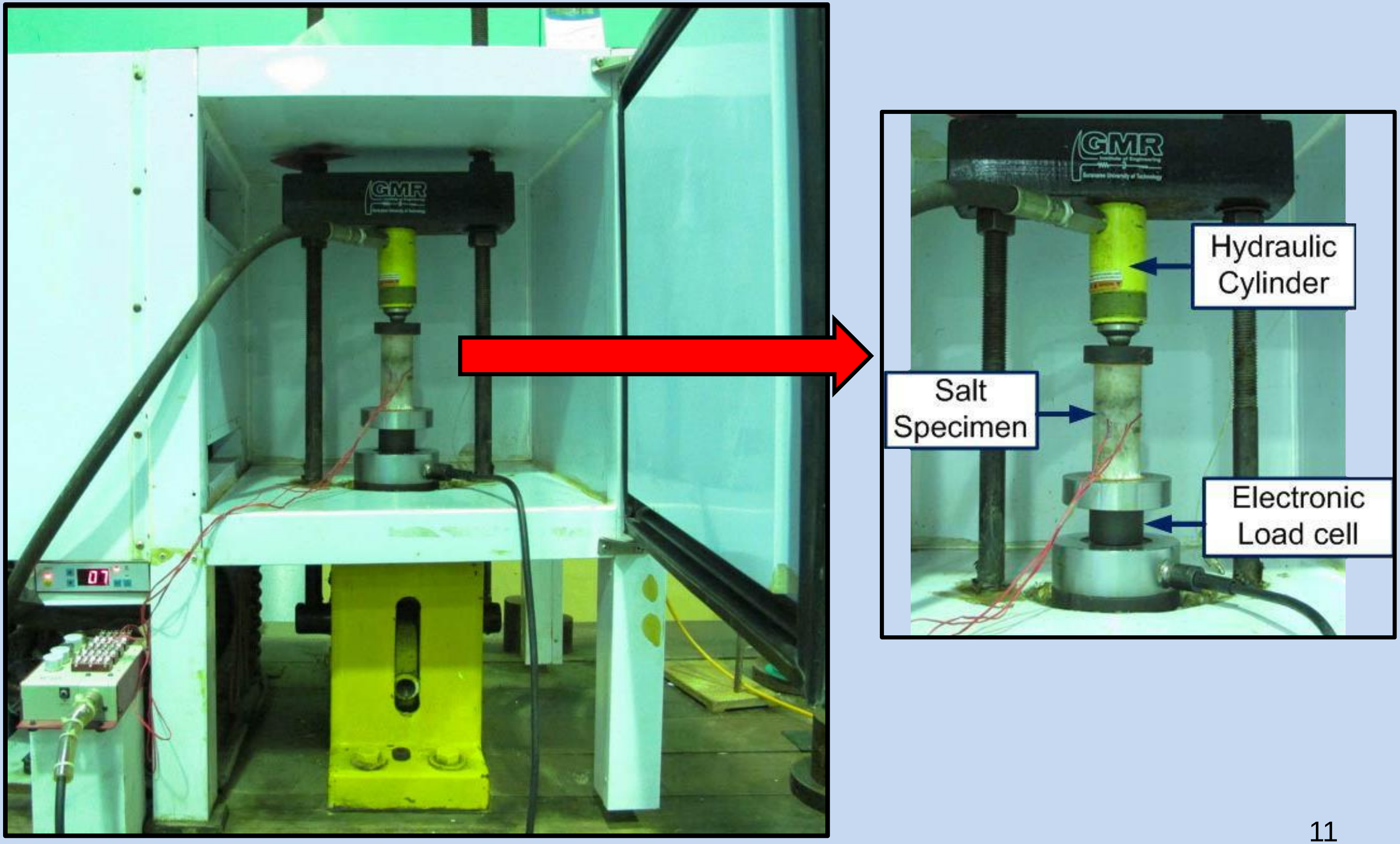
- ❑ The stain energy density criterion is proposed to describe the salt strength

Rock Salt Specimens

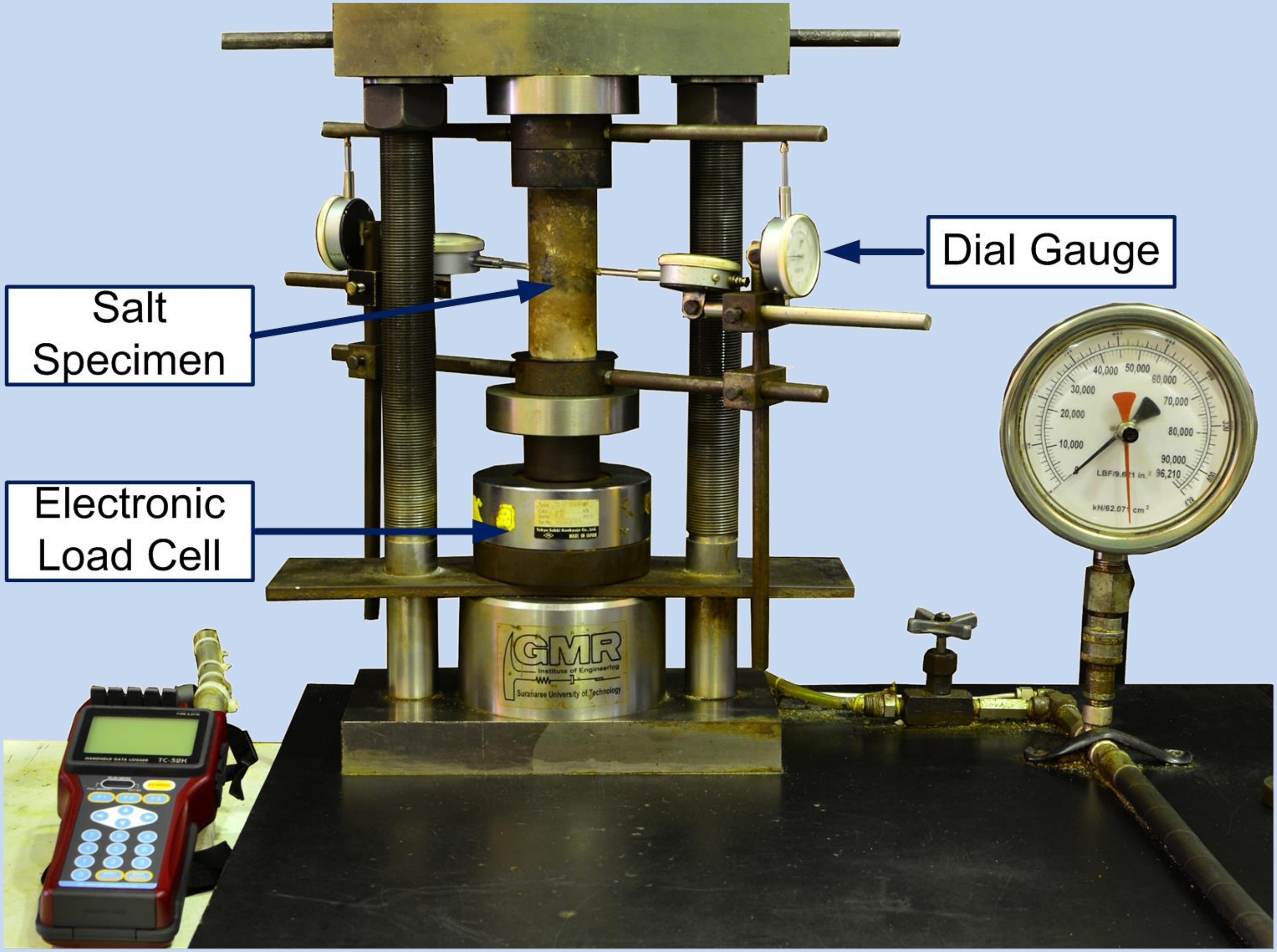
The scope of Testing

- ❑ Uniaxial compression tests performed under constant loading rates and temperature
- ❑ Stress rates ($\partial\sigma_1/\partial t$) : 0.0001, 0.001, 0.01 to 0.1 MPa/s
- ❑ Temperature : 273, 303, 343 and 373 Kelvin (0, 30, 70 and 100°C)

Testing under Low Temperature (273 K)



Testing under Ambient Temperature (303 K)

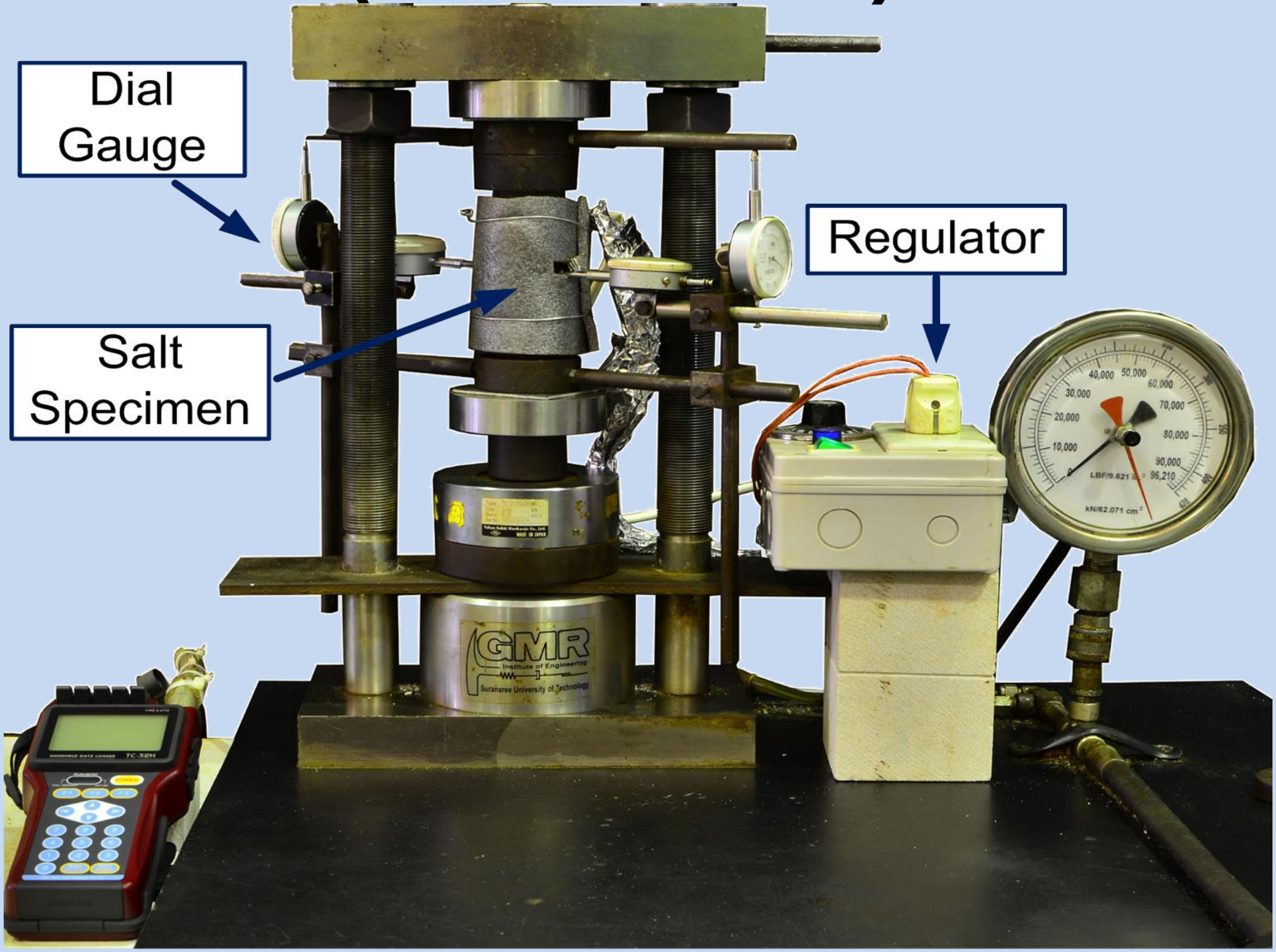


Salt Specimen

Dial Gauge

Electronic Load Cell

Testing under High Temperature (343 and 373 K)



Post-tested specimens

$\square\sigma_1/\square t$ (MPa/s)

0.1 0.01 0.001 0.0001

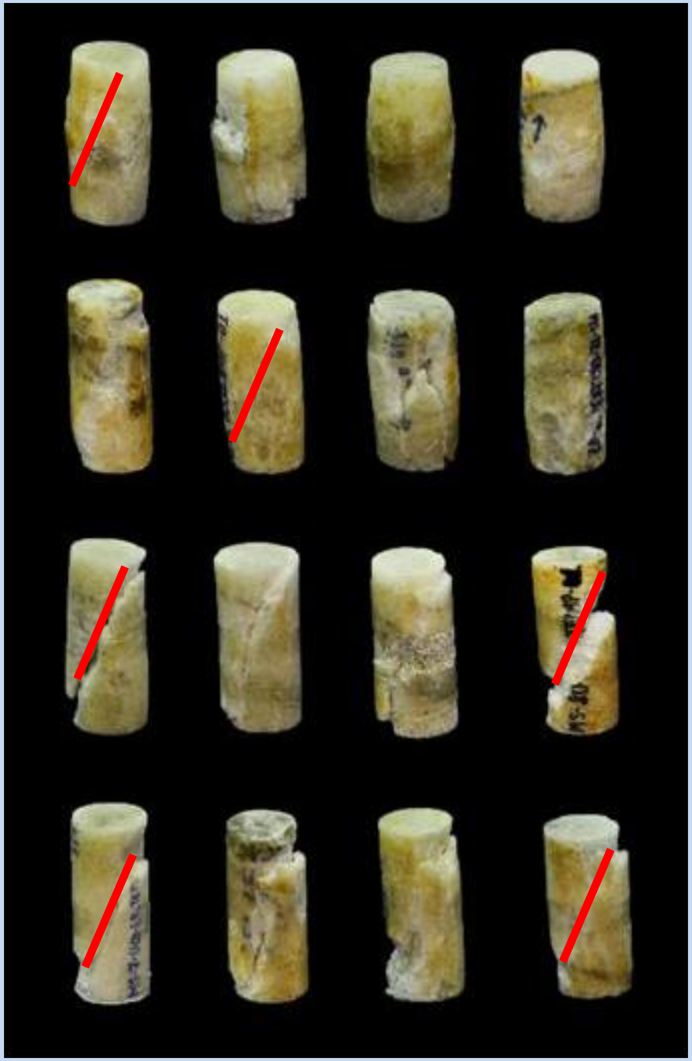
Temperature (K)

373

343

303

273



Test Results

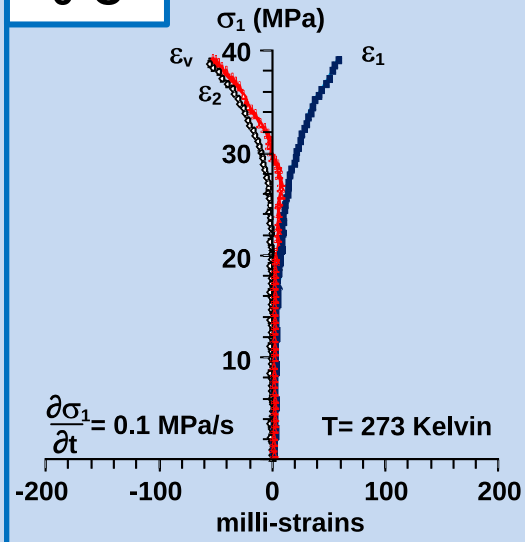
Average Temperature (K)	Stress rate (MPa/s)	Compressive Strength (MPa)	Mean Stress (MPa)
273 (0°C)	0.1	38.79	12.93
	0.01	34.94	11.65
	0.001	33.22	11.07
	0.0001	29.78	9.93
303 (30°C)	0.1	37.23	12.41
	0.01	34.56	11.52
	0.001	32.59	10.86
	0.0001	29.19	9.73
343 (70°C)	0.1	35.78	11.93
	0.01	33.51	11.17
	0.001	29.69	9.90
	0.0001	26.58	8.86
373 (100°C)	0.1	34.60	11.53
	0.01	31.51	10.50
	0.001	28.11	9.37
	0.0001	25.16	8.39

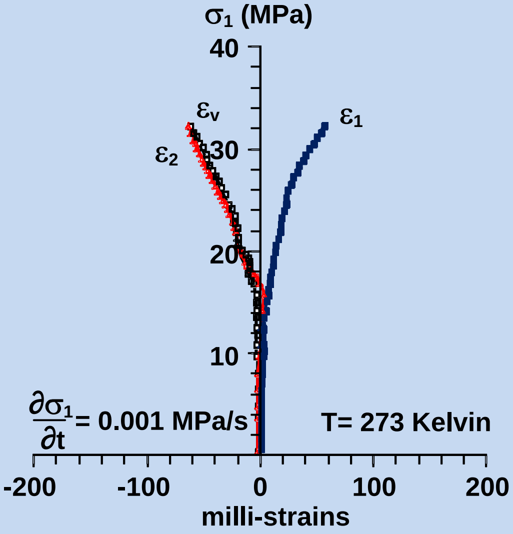
Loading Rate ↓ Uniaxial compressive Strength ↓

Temperature ↑ Uniaxial compressive Strength ↓

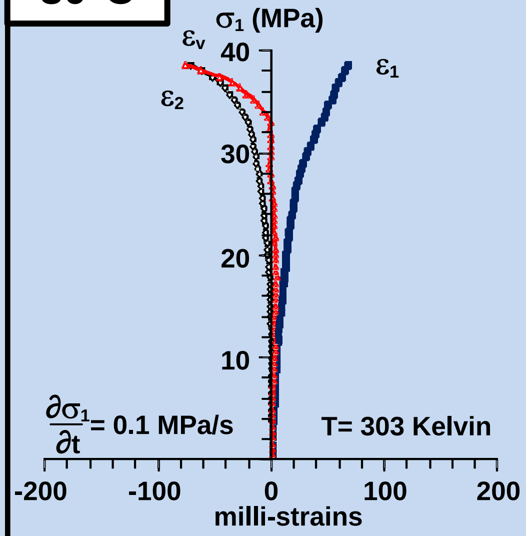
Stress – Strain Curves

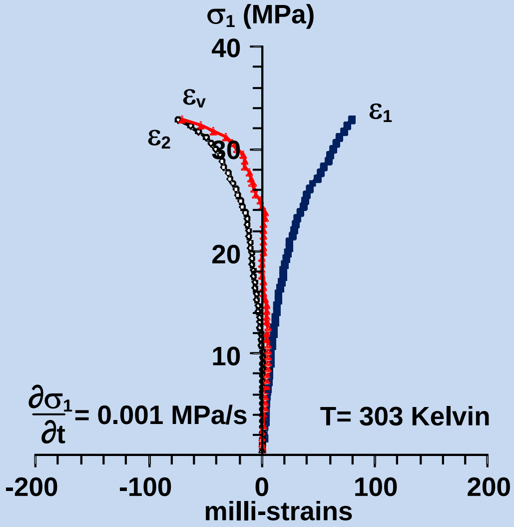
0°C



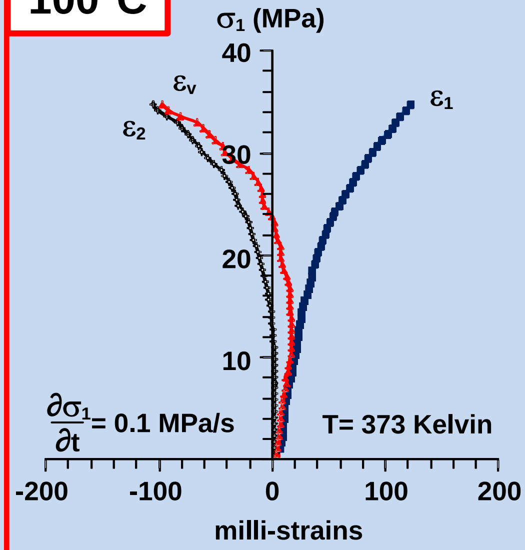


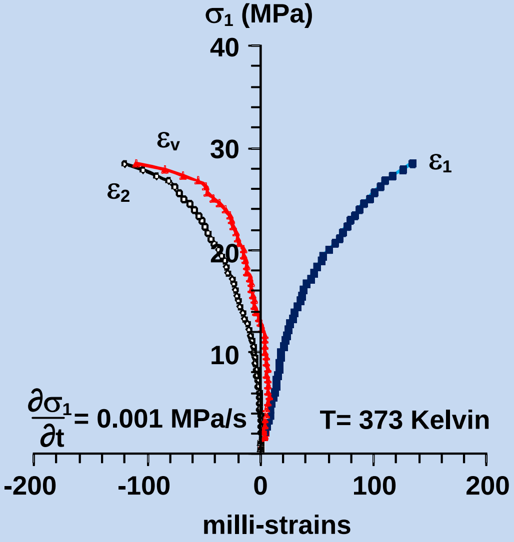
30°C





100°C





Strength Criterion

- The mean stresses (σ_m) and strains (ε_m) and octahedral shear stresses ($\tau_{oct,f}$) and shear strains ($\gamma_{oct,f}$) at failure are determined by (Jaeger *et al*., 2007):

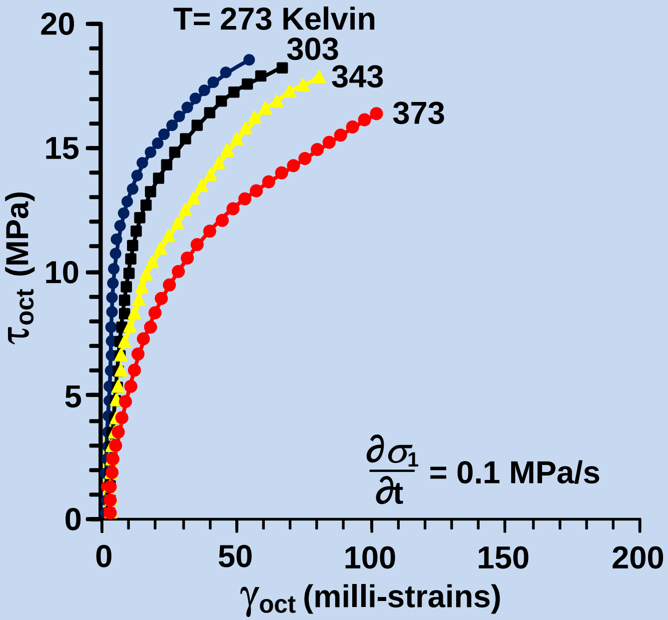
$$\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3 \tag{1}$$

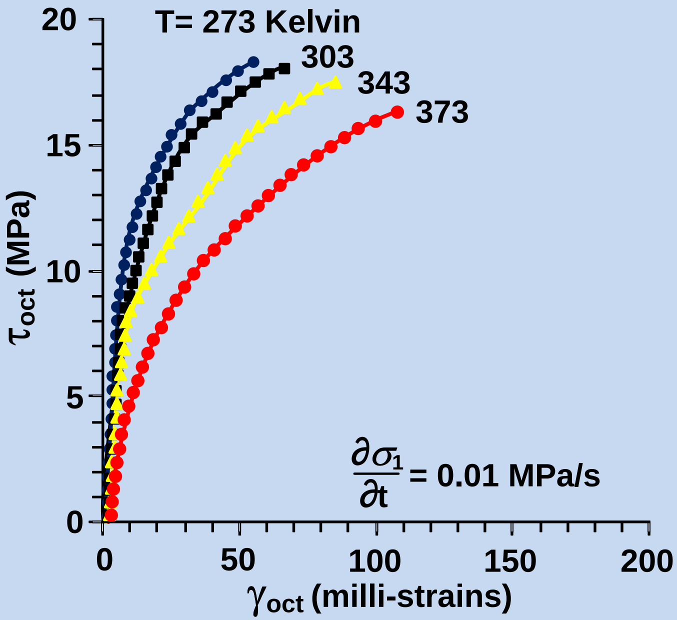
$$\varepsilon_m = (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)/3 \tag{2}$$

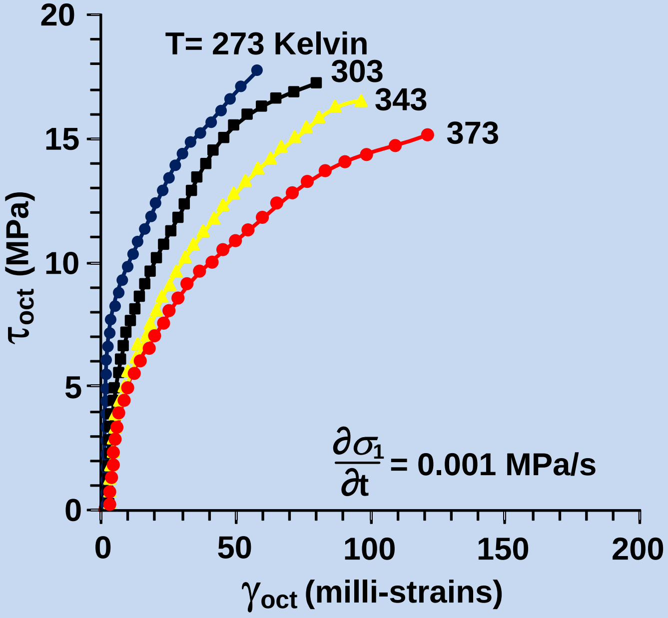
$$\tau_{oct,f} = (1/3)\left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\right]^{1/2} \tag{3}$$

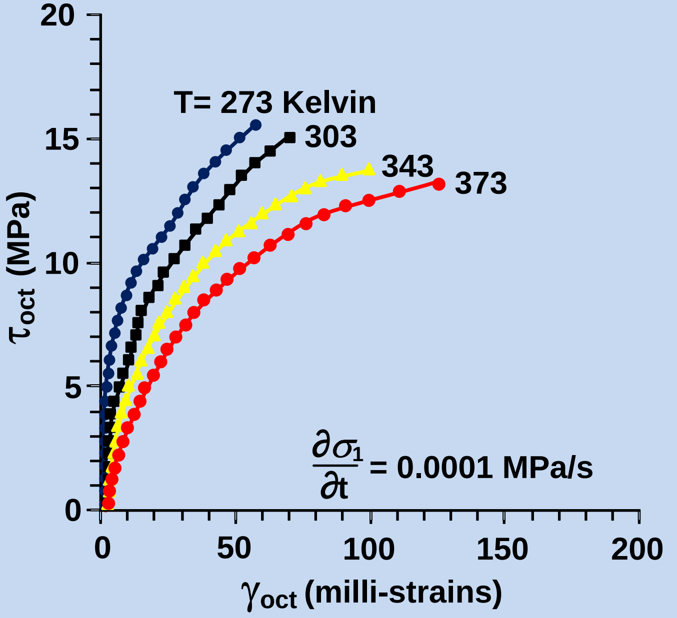
$$\gamma_{oct,f} = (1/3)\left[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2\right]^{1/2} \tag{4}$$

Octahedral Shear Stress – Strain Curves

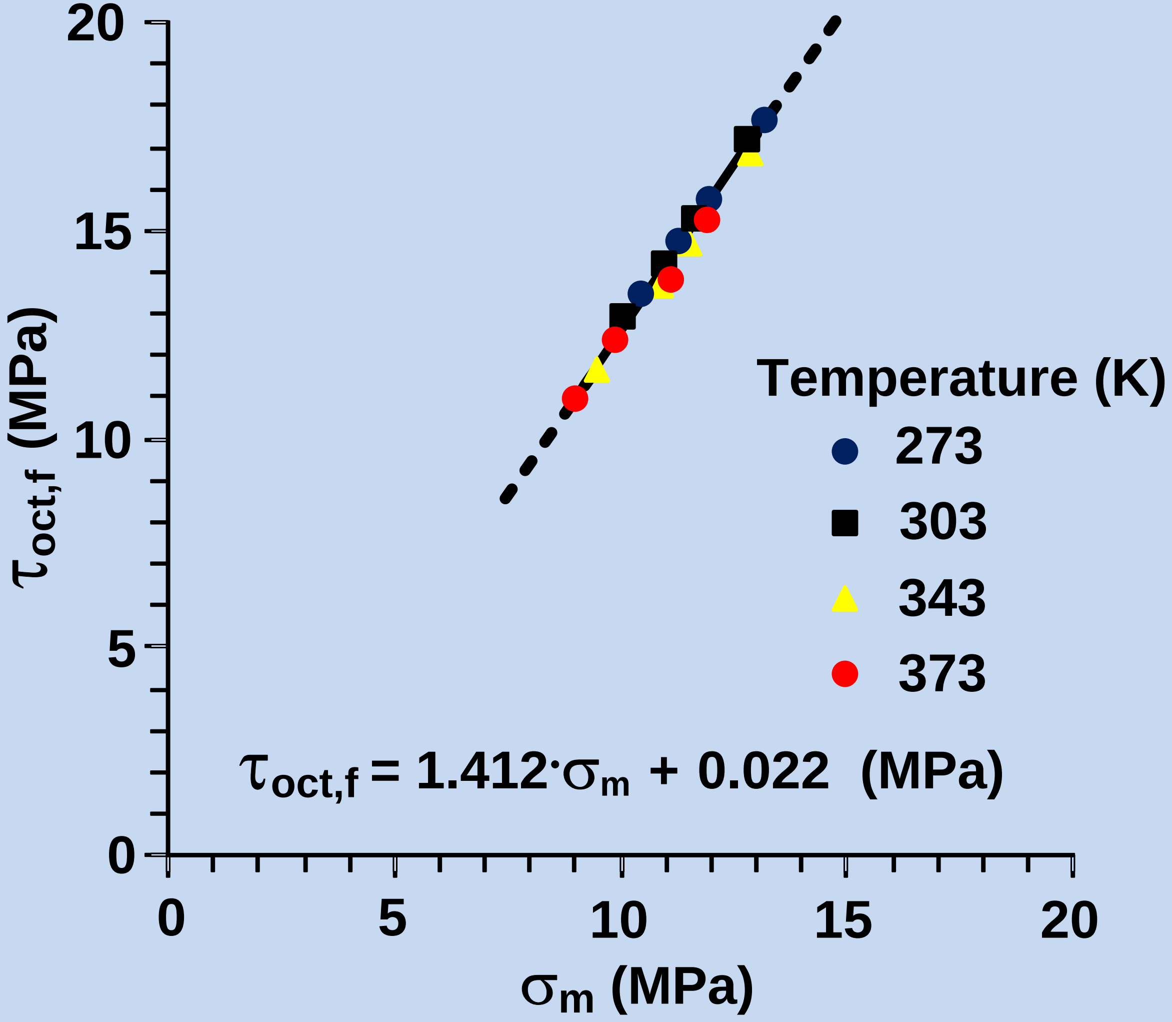








Octahedral Shear Strength vs. Mean Stress



$$\tau_{oct,f} = 1.412 \cdot \sigma_m + 0.022 \ \ \text{(MPa)}$$

Salt Deformation

- ❑ The total compressive strain is composed of two component (Jaeger *et al*., 2007):

$$\varepsilon_c = \varepsilon_c^e + \varepsilon_c^c \qquad (5)$$

where ε_c^e = Elastic strain

ε_c^c = Plastic creep strain

Salt Deformation…

- The elastic strain can be calculated by (Jaeger et al., 2007).

$$\varepsilon_c^c = \frac{\sigma_c}{E} \qquad (6)$$

where σ_c = Compressive stress

E = Elastic modulus

Salt Deformation…

- The exponential creep law is used to describe time-dependent strain of the salt (Yang *et al*., 1999):

$$\varepsilon_c^c = \alpha \cdot \sigma_c^{\beta} \cdot t^{\kappa} \cdot \exp\left(\frac{-\lambda}{T}\right) \qquad (7)$$

where α = Stress constant
β = Stress exponent
κ = Time exponent
λ = Temperature constant
T = Absolute temperature

Salt Deformation…

- ❑ Substituting equations (6) and (7) into (5) we obtain :

$$\varepsilon_c = \frac{\sigma_c}{E} + \alpha \cdot \sigma_c^{\beta} \cdot t^{\kappa} \cdot \exp\left(\frac{-\lambda}{T} \right) \qquad (8)$$

Salt Deformation…

- The creep parameters can be derived in the forms of the octahedral shear strain:

$$\gamma_{oct} = \frac{\tau_{oct}}{2G} + \alpha \cdot \tau_{oct}^{\beta} \cdot t^{\kappa} \cdot \exp\left(\frac{-\lambda}{T}\right) \qquad (9)$$

where γ_{oct} = octahedral shear strain

τ_{oct} = octahedral shear stress

G = shear modulus

λ = temperature constant

Salt Deformation…

- For the stress-rate controlled condition the octahedral shear stress at any loading time (t) can be expressed as:

$$\gamma_{oct}(t) = \frac{\dot{\tau}_{oct}}{2G} + \alpha \cdot \exp\left(\frac{-\lambda}{T}\right) \cdot \tau_{oct}^{\beta} \cdot t^{\beta+\kappa} \qquad (10)$$

- Assuming that the salt elasticity varies linear with temperature (Fuenkajorn, 2012) :

$$G = \psi \cdot T + G_0 \qquad (11)$$

where G_0 = Shear modulus at 0 K.

Salt Deformation…

- Substitute equation (11) into (10) we obtain:

$$\gamma_{oct}(t) = \frac{\dot{\tau}_{oct} \cdot t}{2\left(\psi \cdot T + G_0\right)} + \alpha \cdot \tau_{oct}^{\beta} \cdot t^{\beta+\kappa} \cdot \exp\left(\frac{-\lambda}{T}\right) \qquad (12)$$

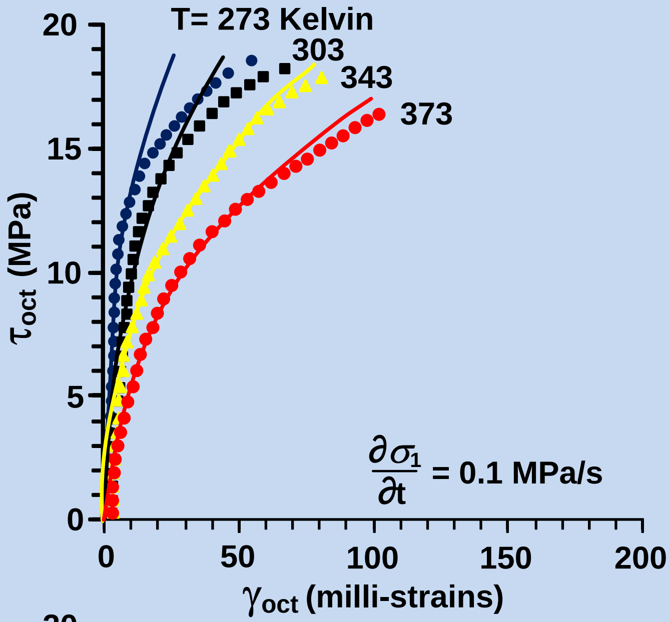
where $\dot{\tau}_{oct}$ = octahedral shear stresses rate

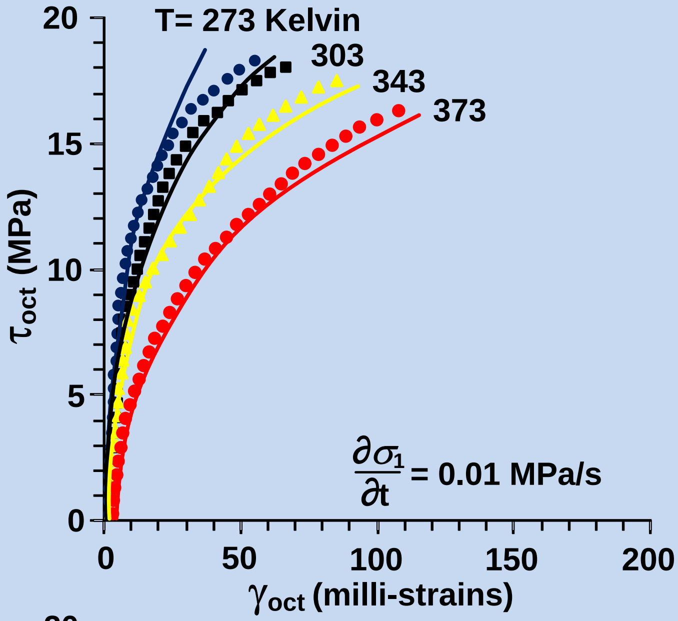
ψ, G_0, α, β, κ, λ are empirical constants

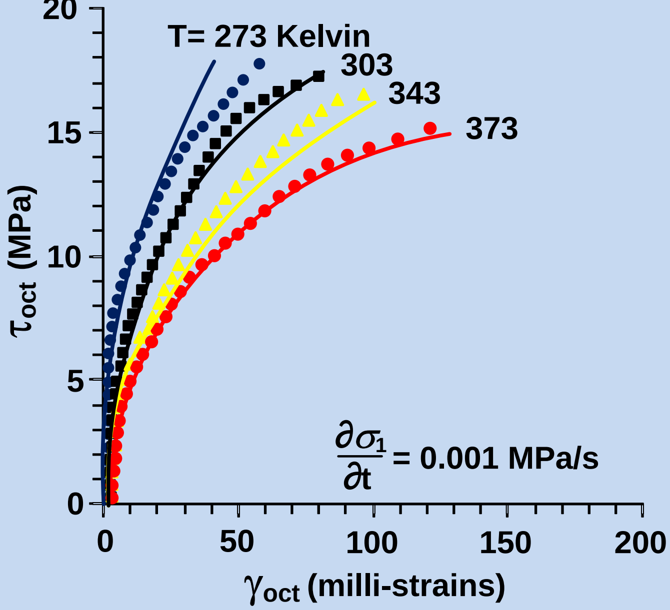
Summary of Calibration

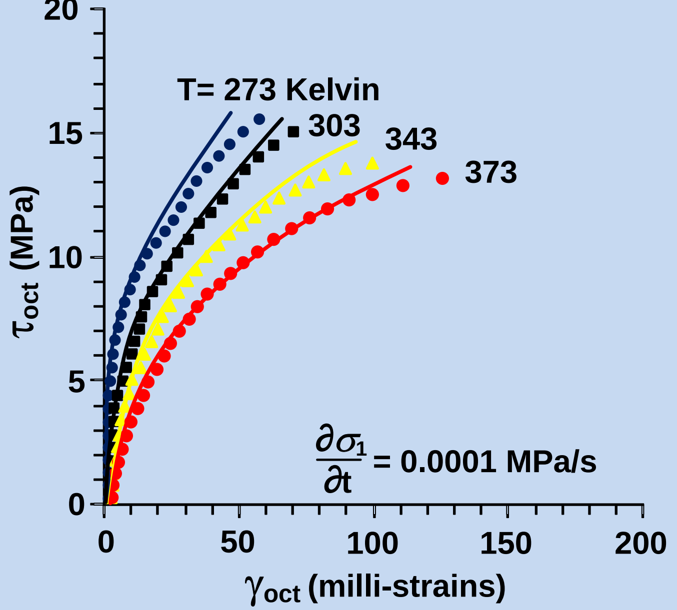
Parameters	**Values**	**R^2**
ψ	-54.04	0.967
G_0	25.82	
α	0.01	
β	2.018	
κ	0.129	
λ	1559.24	

Octahedral Shear Stress – Strain









Empirical Equation of Elastic Parameter

$$E = -0.145 \cdot T + 69.20 \qquad \text{GPa} \quad (13)$$

$$G = -0.054 \cdot T + 25.82 \qquad \text{GPa} \quad (14)$$

$$\nu = (2 \times 10^{-4}) \cdot T + 0.26 \qquad (15)$$

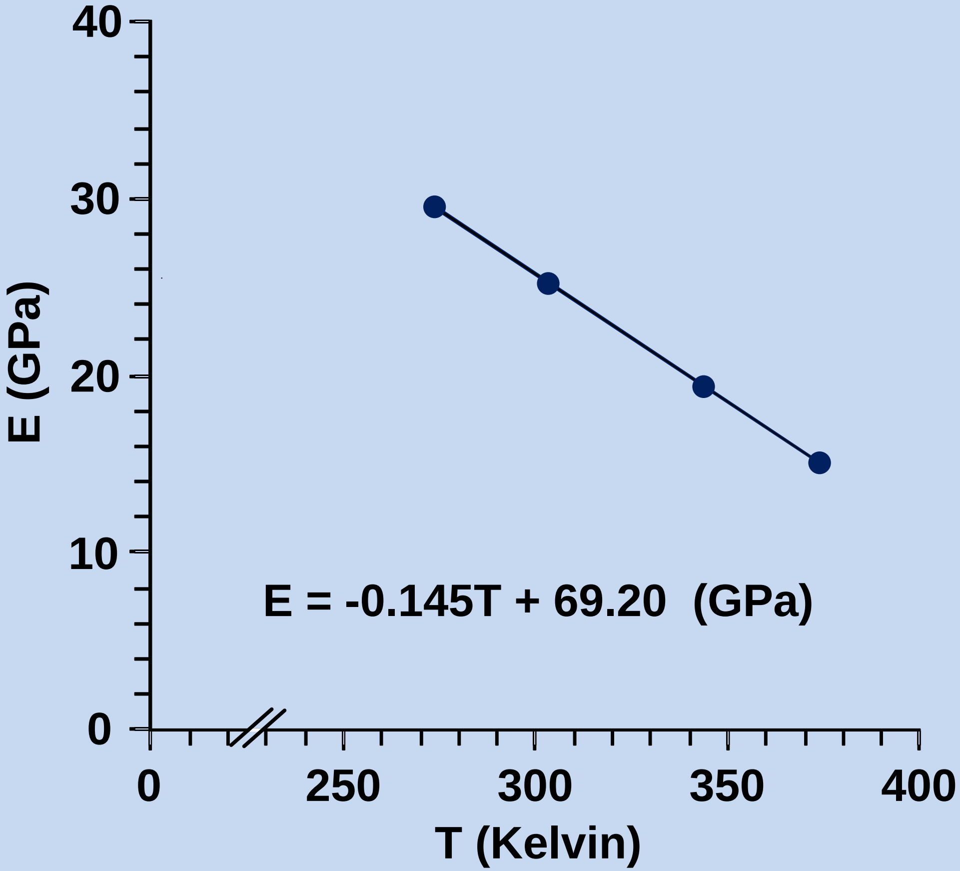
where E = Elastic Modulus

G = Shear Modulus

ν = Poisson’s ratio

T = Temperature

Elastic Modulus vs. Temperature

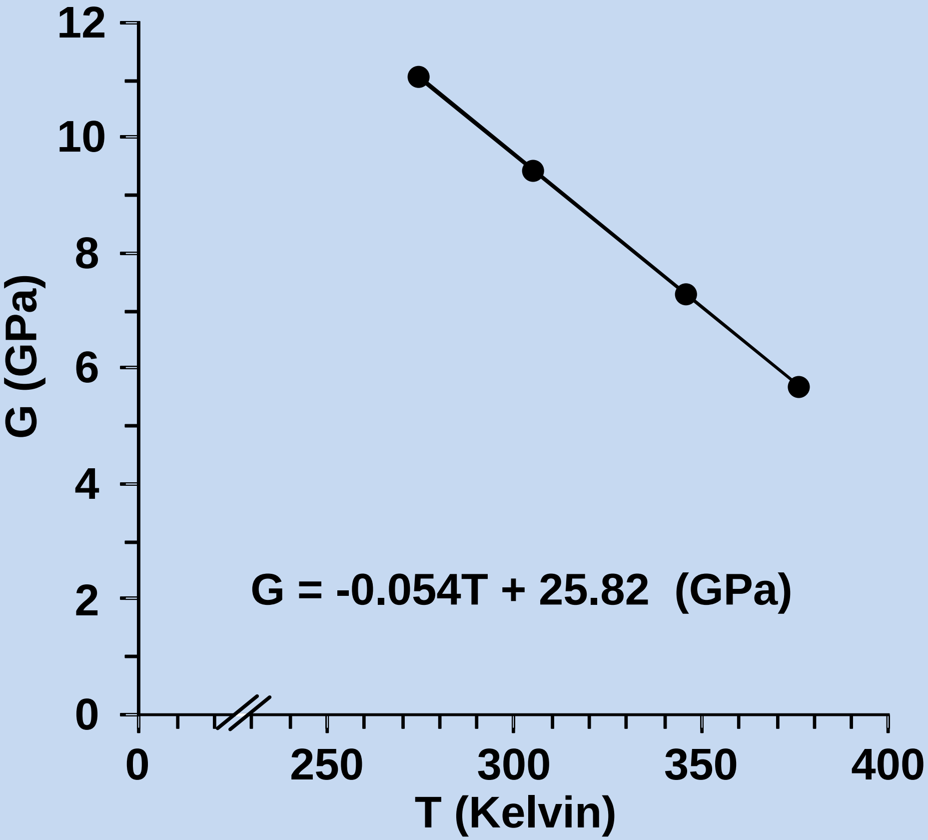


$E = -0.145T + 69.20$ (GPa)

$E = 15 - 29$ GPa

E decreases with temperature

Shear Modulus vs. Temperature

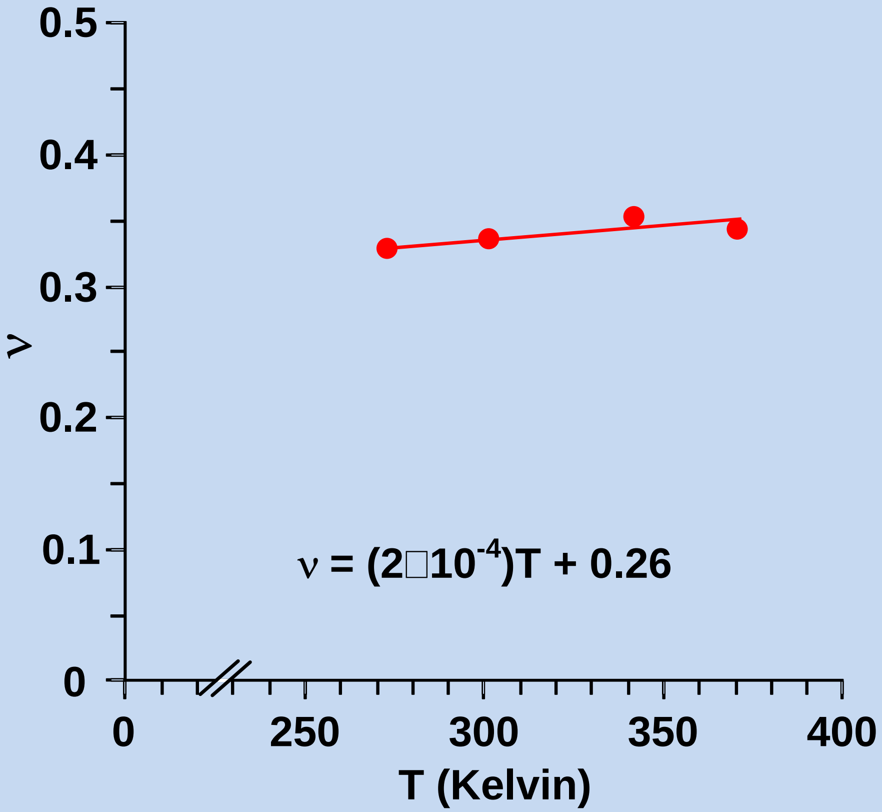


G = 5 - 11 GPa

G decreases with temperature

Poisson’s Ratio vs. Temperature

Poisson’s Ratio = 0.32 - 0.35



Independent of loading rate and temperature

Strain Energy Density

- ❑ Distortional strain energy at failure (W_d) can be calculated from the octahedral shear stresses and strains (Jaeger & Cook, 1979):

$$W_d = (3/2) \cdot \tau_{oct} \cdot \gamma_{oct} \qquad (13)$$

- ❑ Mean strain energy at failure (W_m) calculated from the mean stresses and strains:

$$W_m = (3/2) \cdot \sigma_m \cdot \varepsilon_m \qquad (14)$$

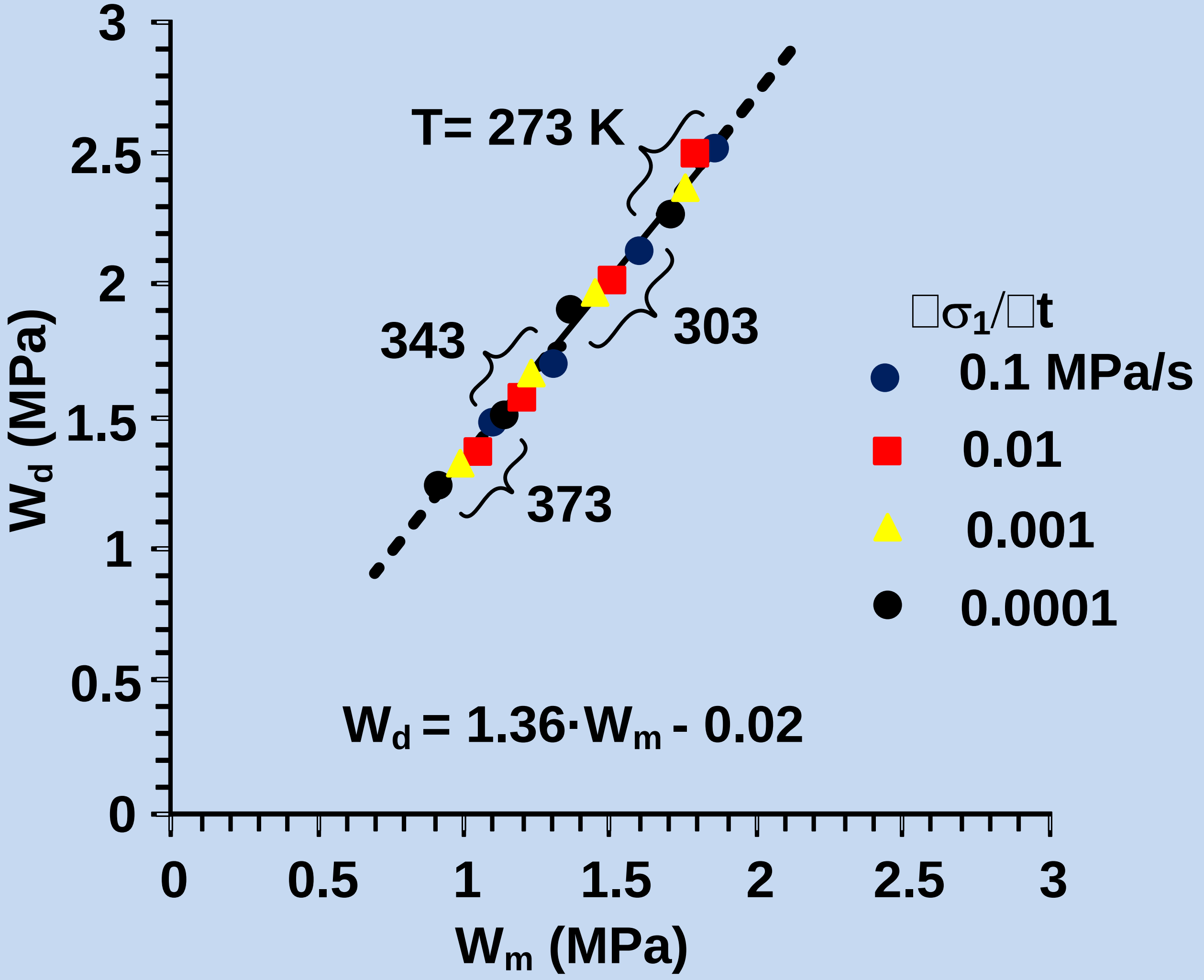
Strain Energy Density Criterion

- Distortional strain energy at failure (W_d) can be derived as a function of the mean strain energy density at failure (W_m):

$$W_d = \omega \cdot W_m - \upsilon \qquad (15)$$

where ω and υ are empirical constant

Distortional vs. Mean Strain Energy



Discussions and Conclusions

- The decrease of the salt strength as the temperature increases suggests that the applied thermal energy before the mechanical testing makes the salt weaker, and more plastic.

- The failure stresses increase with the loading rates, these agree with the experimental results by Fuenkajorn *et al*. (2012) and Dubey and Gairola (2005).

- ❑ The elastic and shear modulus linearly decrease with increasing temperature. The Poisson’s ratio however tends to be independent of the temperature.
- ❑ For the same temperature the strain increases with low loading rate. For the same loading rate, the strains increase with increasing temperature.

Discussions and Conclusions

- The exponential creep law agrees with the test results in terms of the octahedral shear strains as a function of time

- The distortion strain energy criterion can be describe the salt strength under varied stress rates and temperatures

- The criterion can be used to determine the stability of rock salt around compressed-air or gas storage cavern

Acknowledgements

Funded by Suranaree University of Technology
and by the Higher Education Promotion
and National Research University of Thailand