Effects of Loading Rate and Pore Pressure on Compressive Strength of Rocks

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Outline

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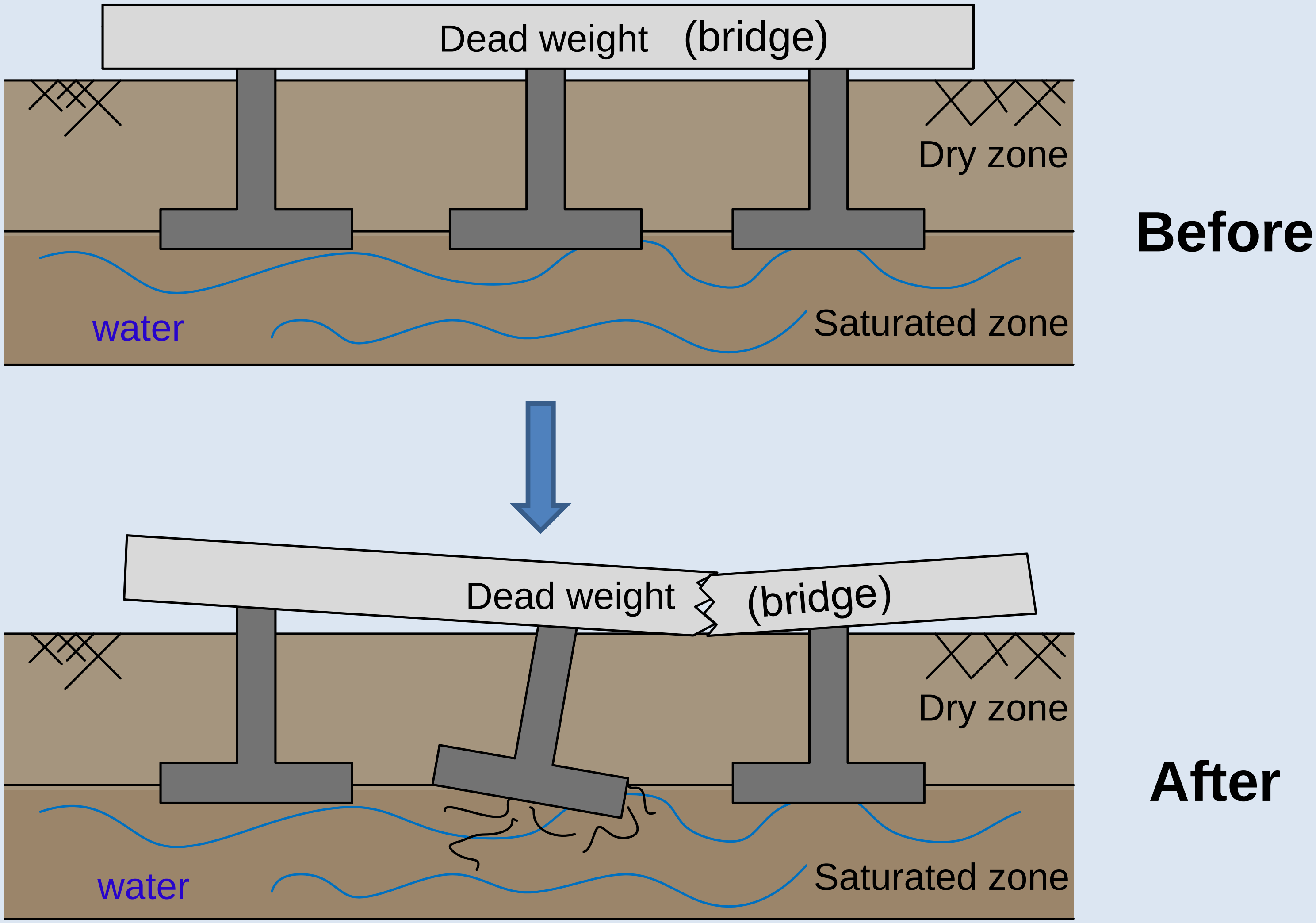
- Objectives
- Rock Specimens and Preparation
- Laboratory Testing
- Test Results
- Conclusions and Discussions

Background and Rationale



Background and Rationale…

Bhumipol Dam

http://roggerroll.wordpress.com

Srinakarin Dam

http://www.thai-tour.com

Background and Rationale…

- Masuda (2001) studies the effects of water on rock strength in granite and andesite.

- The failure strength decreased linearly as the logarithm of the strain rate decreased.

Background and Rationale…

- Cobanoglu and Celik (2012) determine the uniaxial compressive strength tested in the dry and saturated conditions.

- The average saturated to dry strength ratios of travertines is 0.922.

Background and Rationale…

- Vasarhelyi (2003) determined the unconfined compressive strength of British sandstones.

- Statistically the saturated UCS is 75.6% of the dry ($UCS_{sat} = 0.759UCS_{dry}$), while the saturated tangent and secant moduli are 76.1 and 79.0% of the dry samples respectively.

Background and Rationale…

- Li et al. (2012) study the influence of water content and anisotropy on the strength and deformability of sedimentary rocks.

- The influence of water are reflected as a reduction of Young's modulus and increase of Poisson's ratio.

Objectives

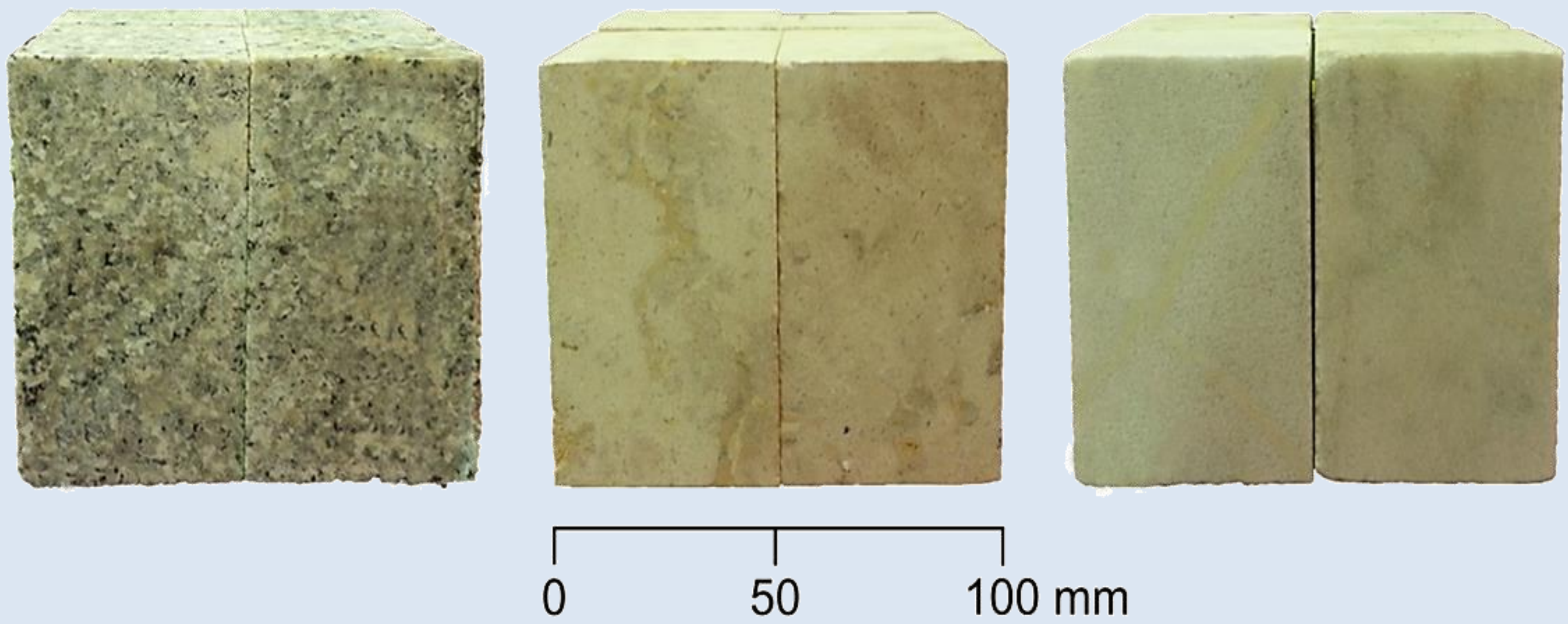
- Determine the effects of pore pressure on the compressive strength and elastic properties of granite, marl and marble.

- Determine stress rate and confining pressure effect on the rock compressive strength.

- Assess the predictive capability of three-dimensional failure criteria that can be applied in the design and stability analysis of rock embankments and foundations under dry and saturated conditions.

Rock Specimens and Preparation

Granite Marl Marble



Rock Specimens and Preparation…

The specimens are submerged under water in a pressure vacuum chamber.

Laboratory Testing

❑ Water Content

Every two hours

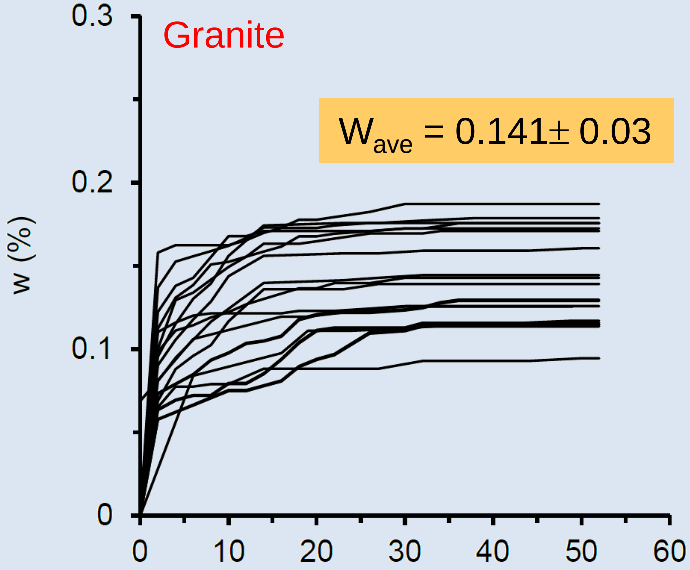
The water content (W) in rock can be calculated by:

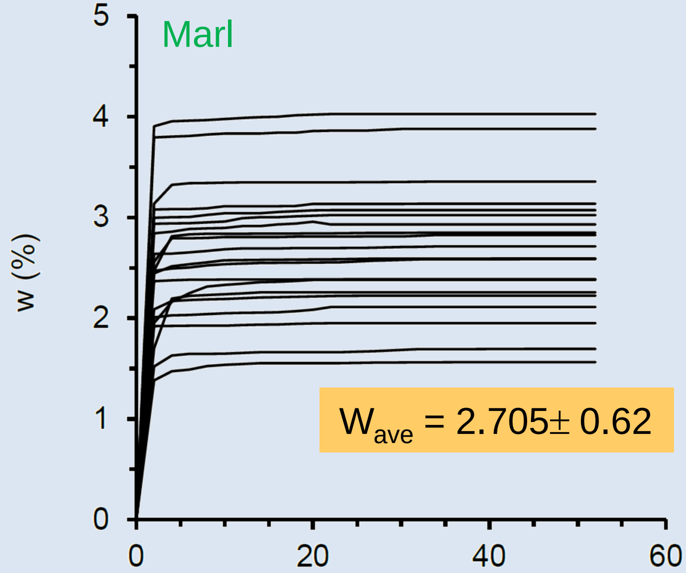
$$W = (W_w / W_s) \times 100 \qquad (1)$$

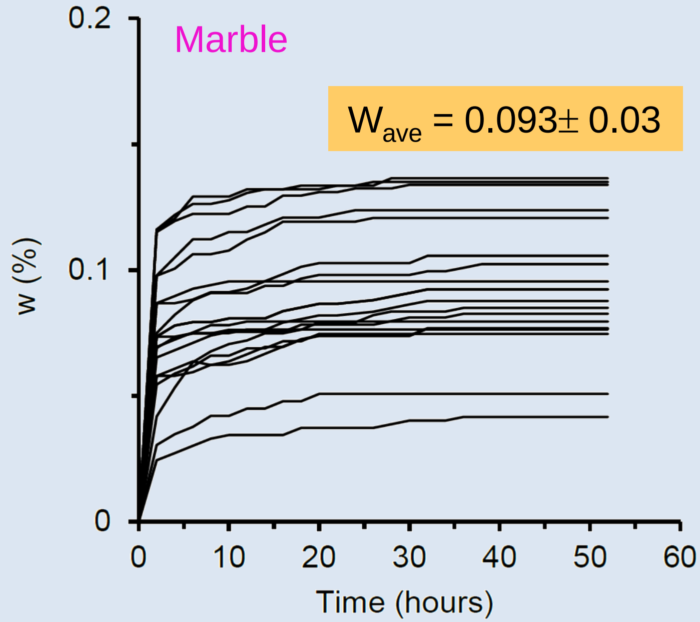
where W_w = mass of water in rock

W_s = dry mass of rock

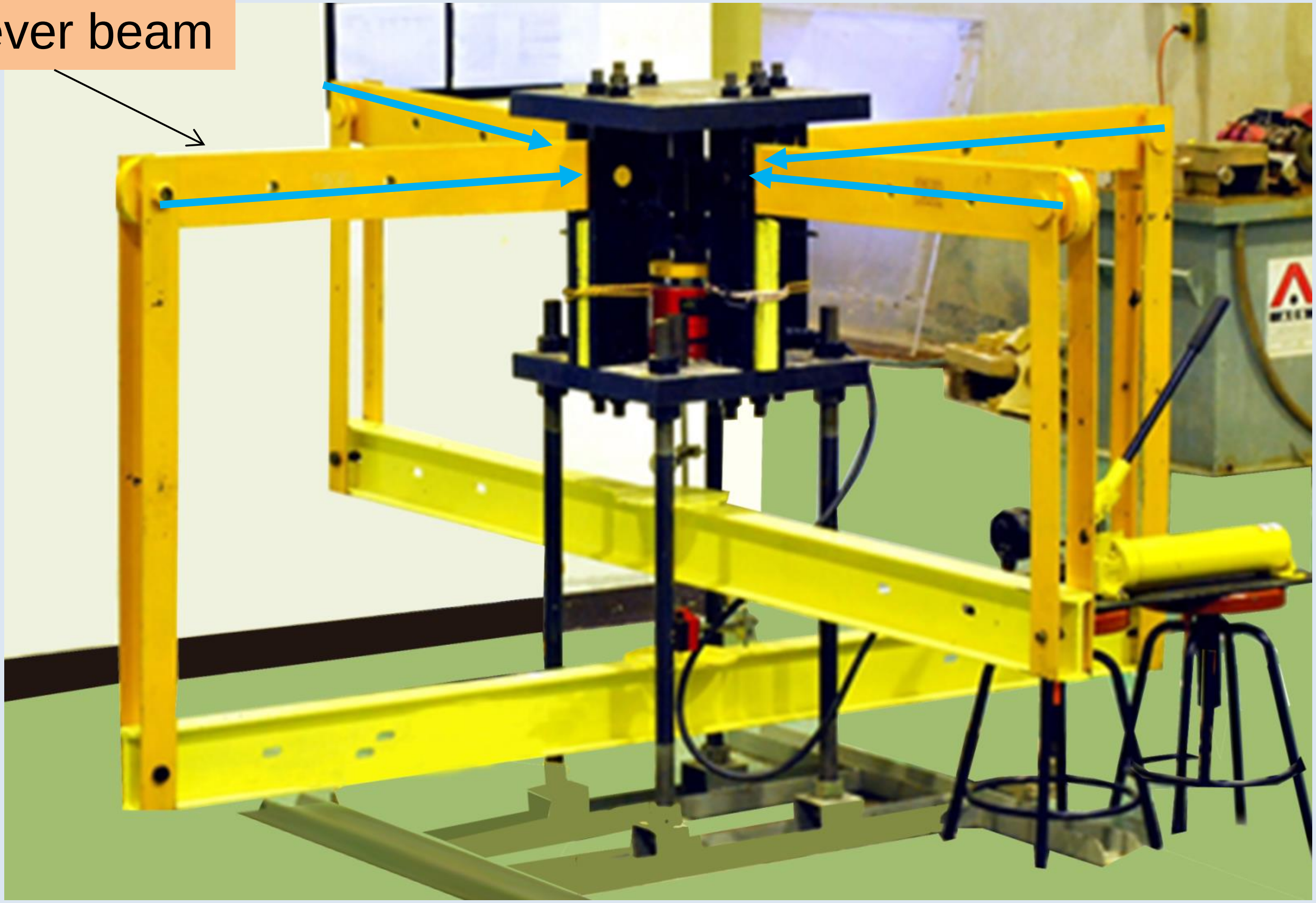
Laboratory Testing…







Laboratory Testing…



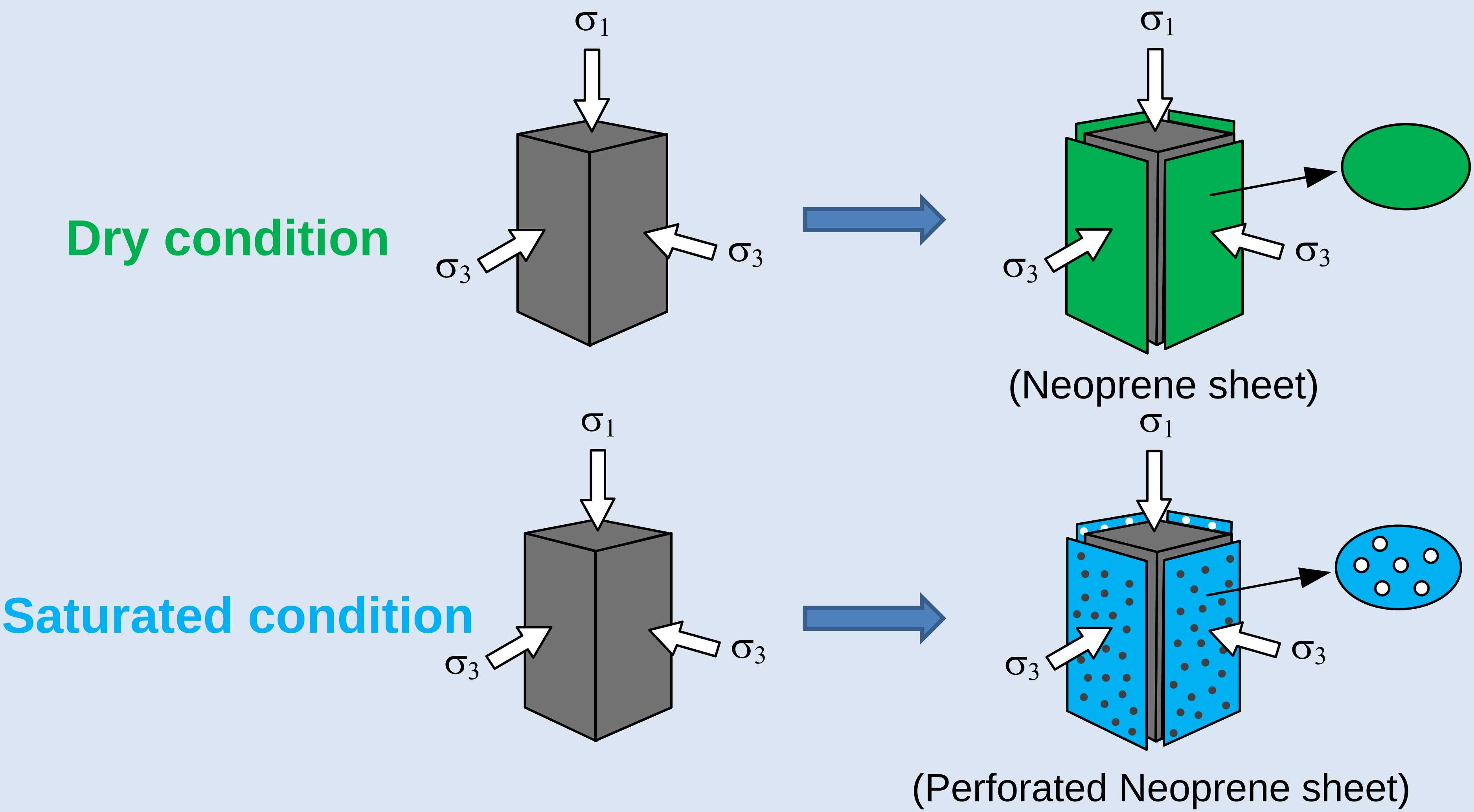
A polyaxial load frame (Fuenkajorn & Kenkhunthod, 2010)

Laboratory Testing…

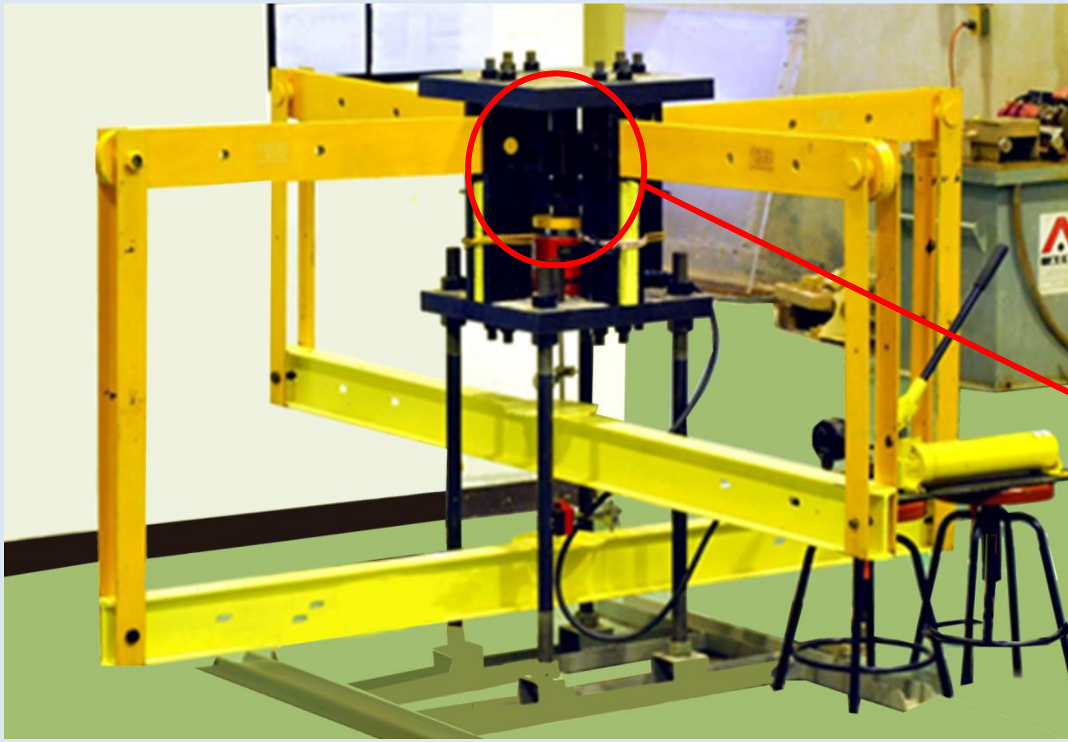
- Applied loading rate varies from 0.001, 0.01, 0.1, 1 and 10 MPa/s

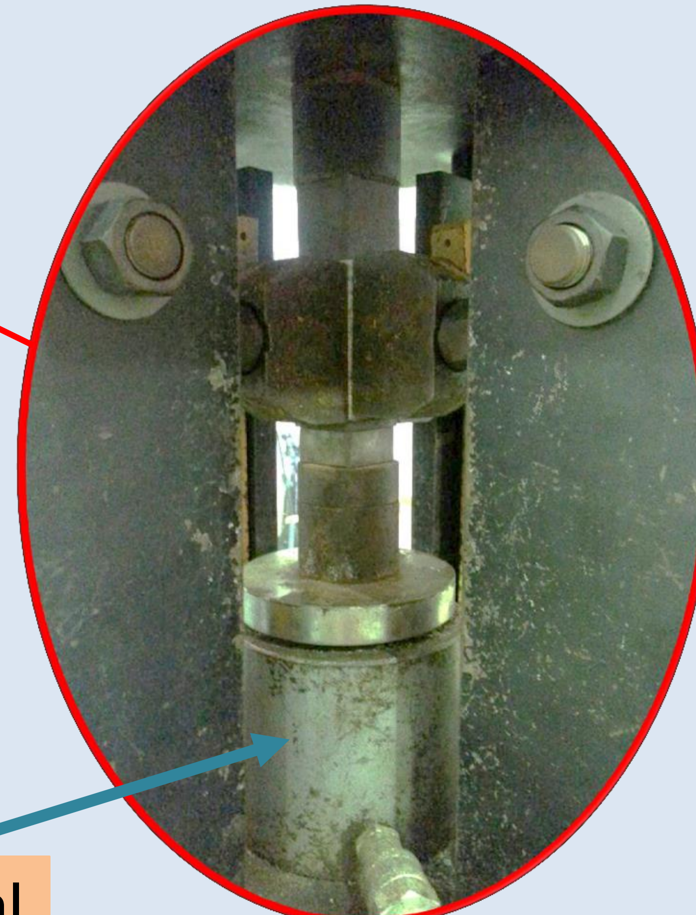
- Applied confining pressure (σ_3) varies from 0, 3, 7, 12 MPa.

Laboratory Testing…



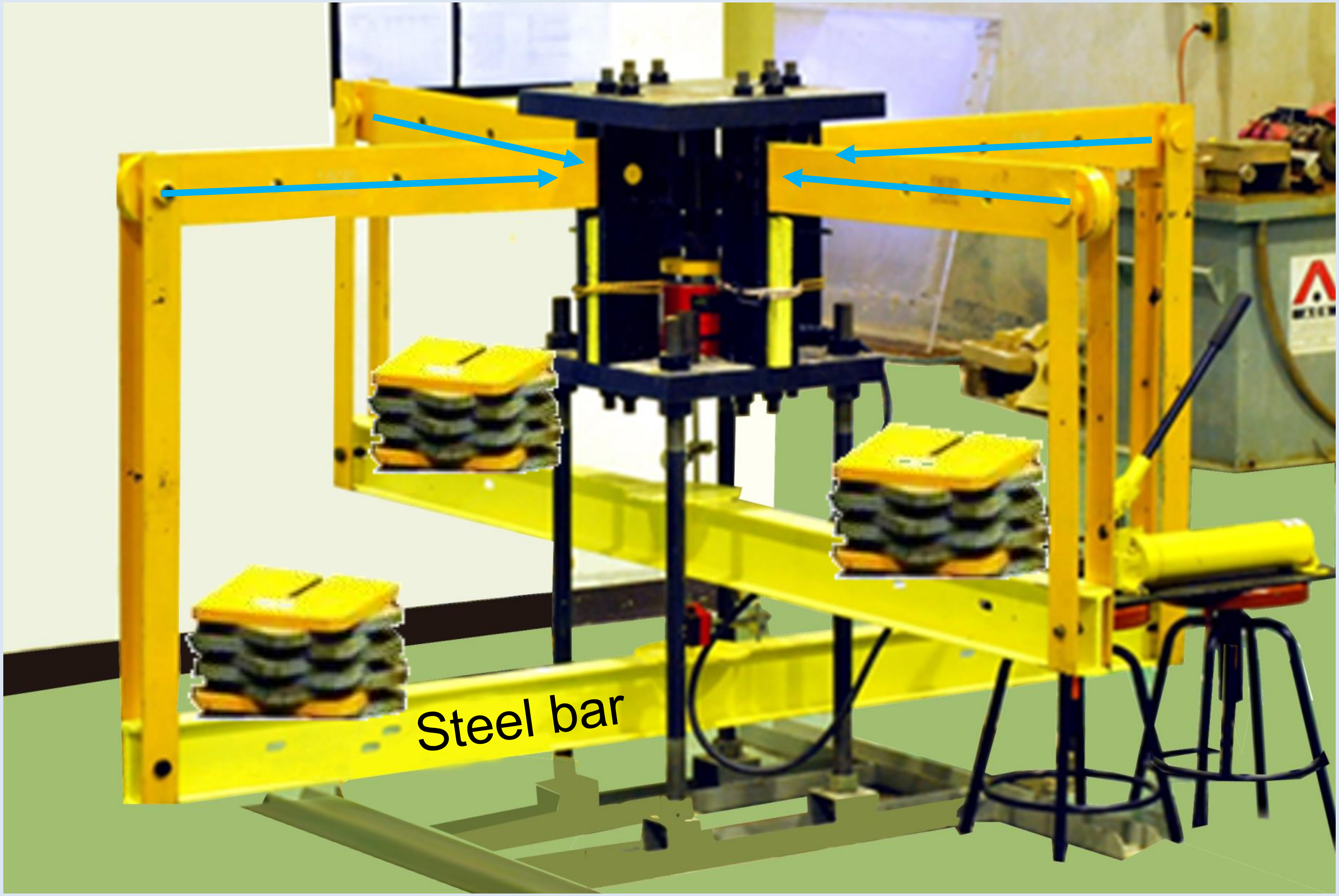
Laboratory Testing…



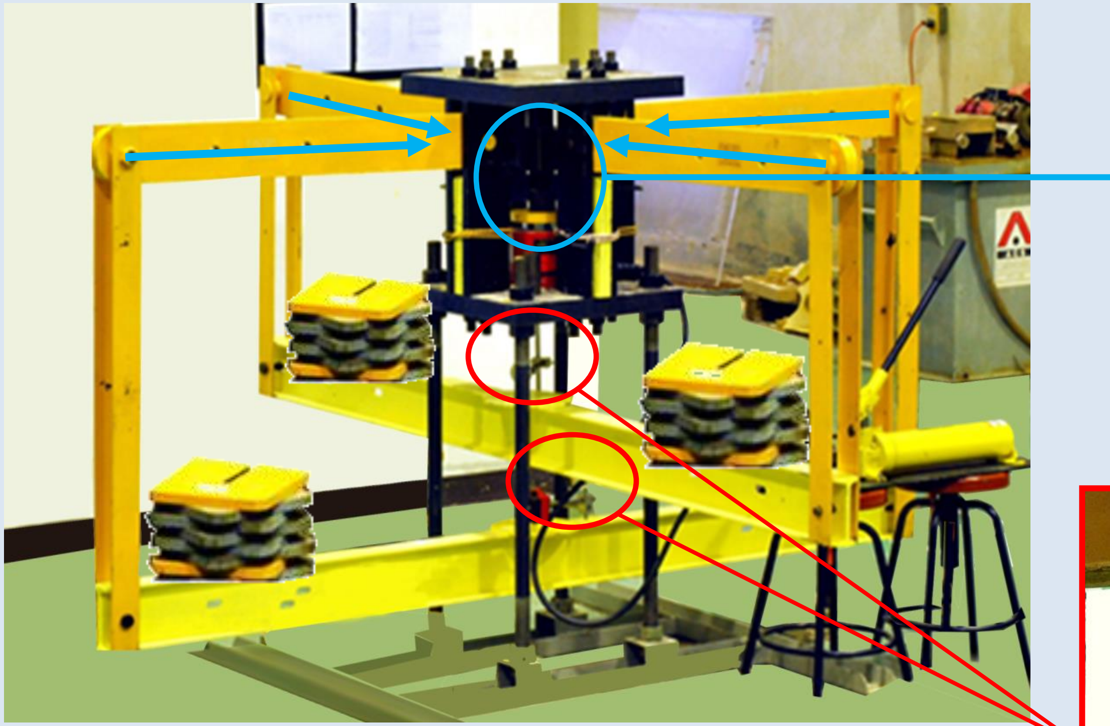


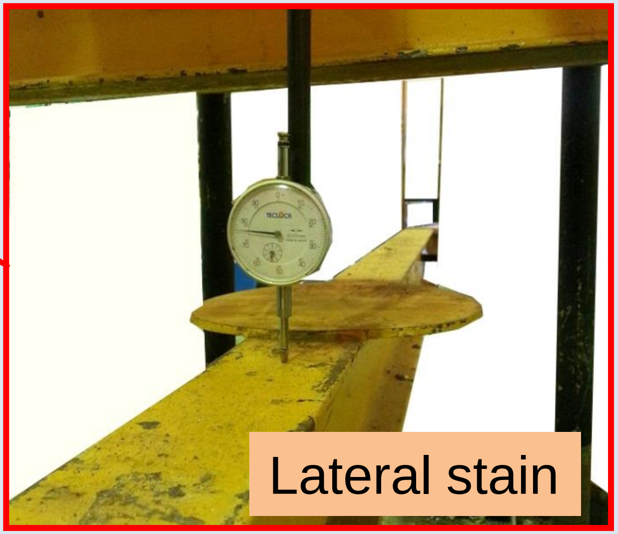
Hydraulic Cylindrical

Laboratory Testing…



Laboratory Testing…





Laboratory Testing…

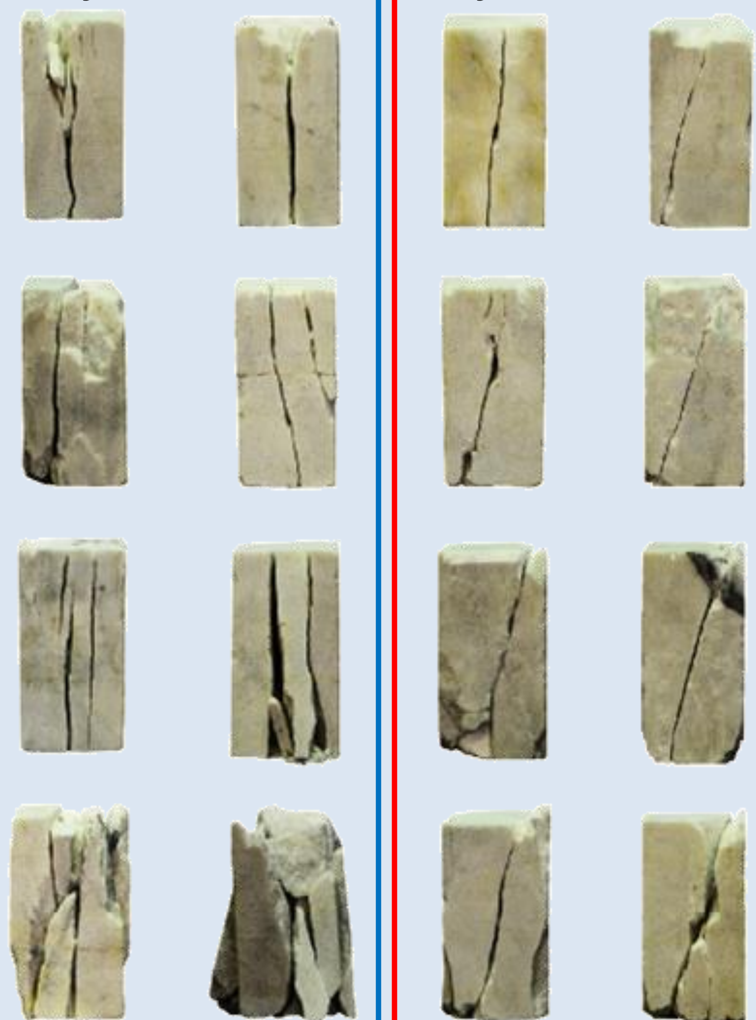
- Axial stresses (σ_1) is increased until failure occurs.

- The axial strain, lateral strain, and time are monitored.

Rock Samples after Testing

$\dot{\sigma}_1$ = 1 MPa/s — Dry, Saturated

$\dot{\sigma}_1$ = 0.001 MPa/s — Dry, Saturated



σ_3 = 0 MPa

3 MPa

7 MPa

12 MPa

Extension failure mode

Shear failure mode

Test Results

Test Data

❑ Strength of rock
Maximum compressive strength

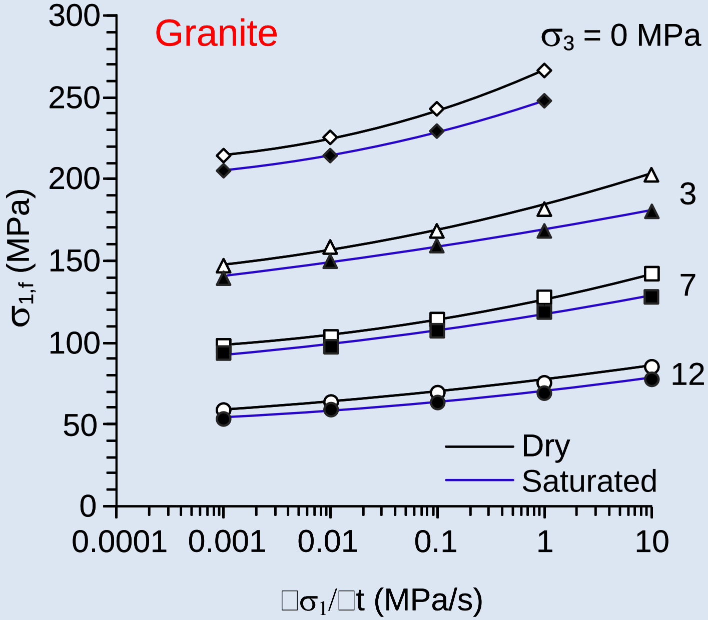
❑ Coulomb criterion
- Shear strength, τ
- Cohesion, c
- Internal friction angle, ϕ

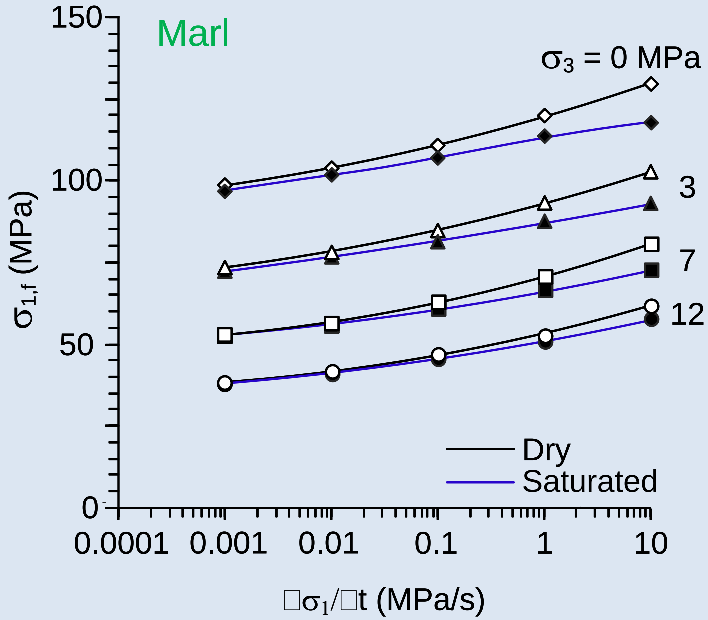
❑ Elastic parameters
- Elastic modulus, E
- Poisson's ratio, ν

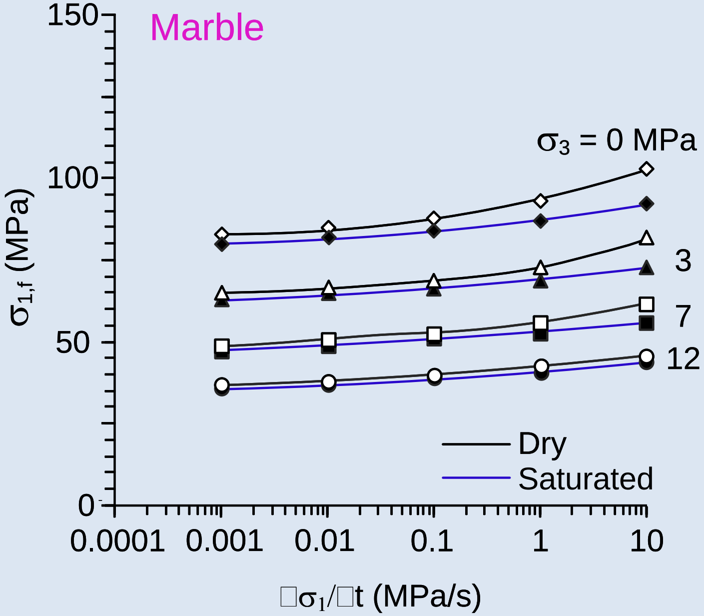
❑ Strain energy density criterion
- Distortional strain energy, W_d
- Mean strain energy, W_m

Data Analysis

Test Results…



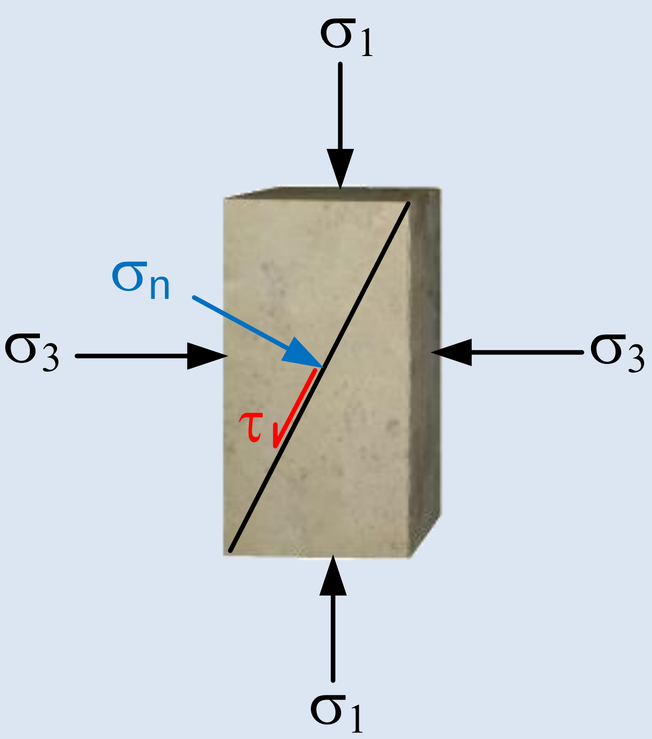




Test Results…

Coulomb Criterion

The shear strength (τ) can be represented by this equation



$$\tau = c + \sigma_n \tan \phi \qquad (2)$$

where σ_n = the normal stress,

c = the cohesion,

ϕ = friction angle.

Test Results…

Cohesion

$$c = b\,((1-\sin\phi) / (2-\cos\phi)) \qquad (3)$$

Internal friction angle

$$\phi = \arcsin\,(m-1) / (m+1) \qquad (4)$$

$$c = \chi \cdot \ln(\partial\sigma_1/\partial t) + \psi \qquad (5)$$

$$\phi = \omega \cdot \ln(\partial\sigma_1/\partial t) + \iota \qquad (6)$$

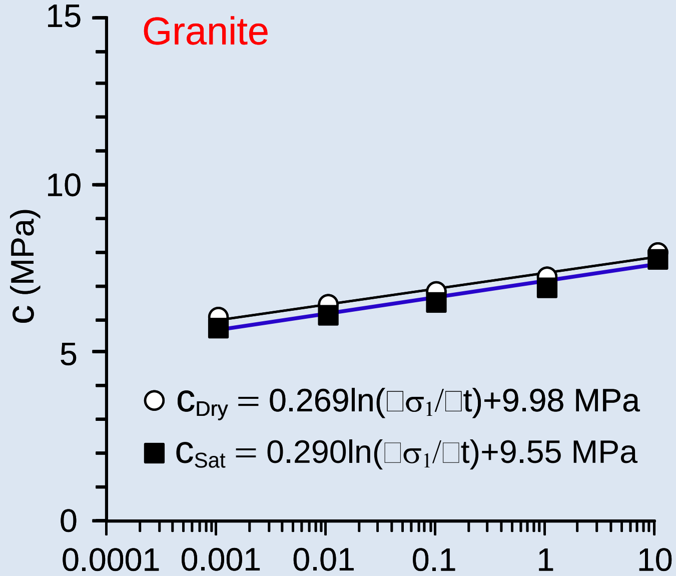
The parameters χ, γ, ω, ι are empirical parameters.

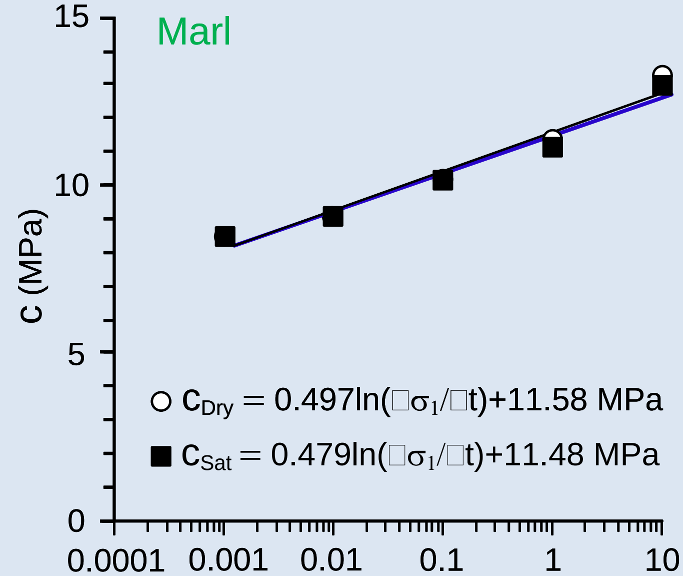
Test Results…

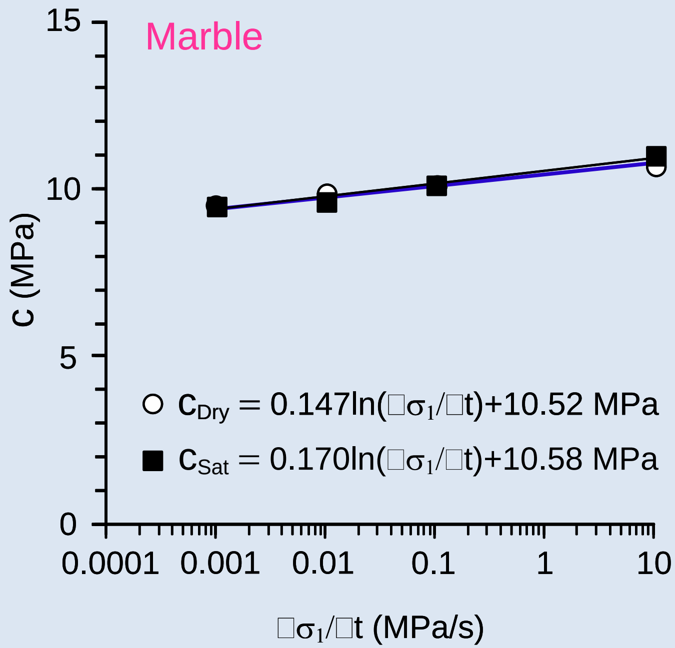
Substituting equations (5) and (6) into (2) Equation (2) can be rewritten as

$$\tau = [\ \chi \cdot \ln(\partial_1 / \partial t) + \psi] + \sigma_n \tan [\ \omega \cdot \ln(\partial_1 / \partial t) + \iota] \quad (7)$$

Test Results…







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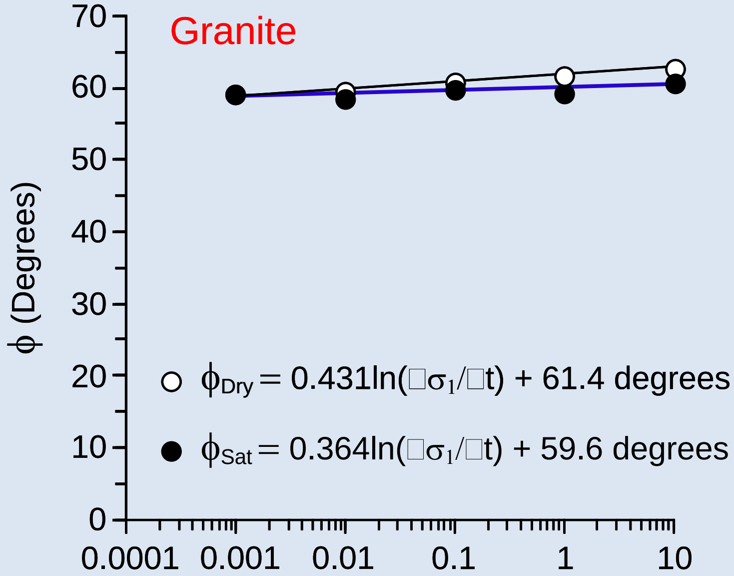
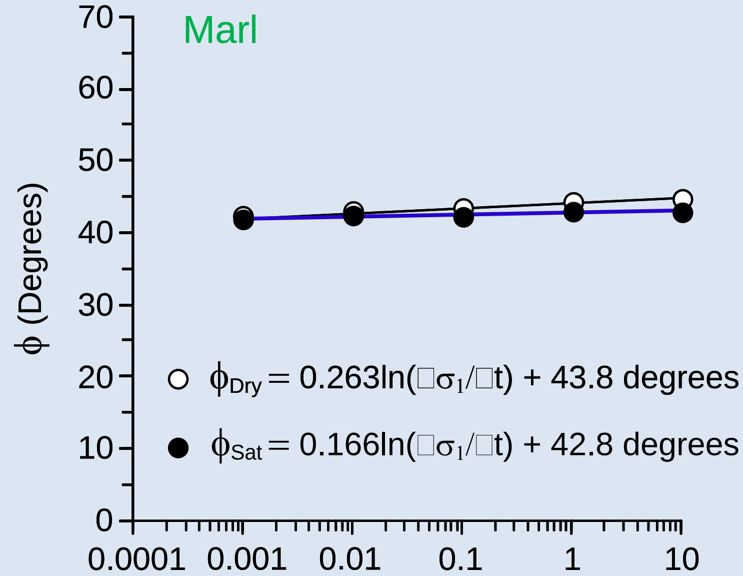
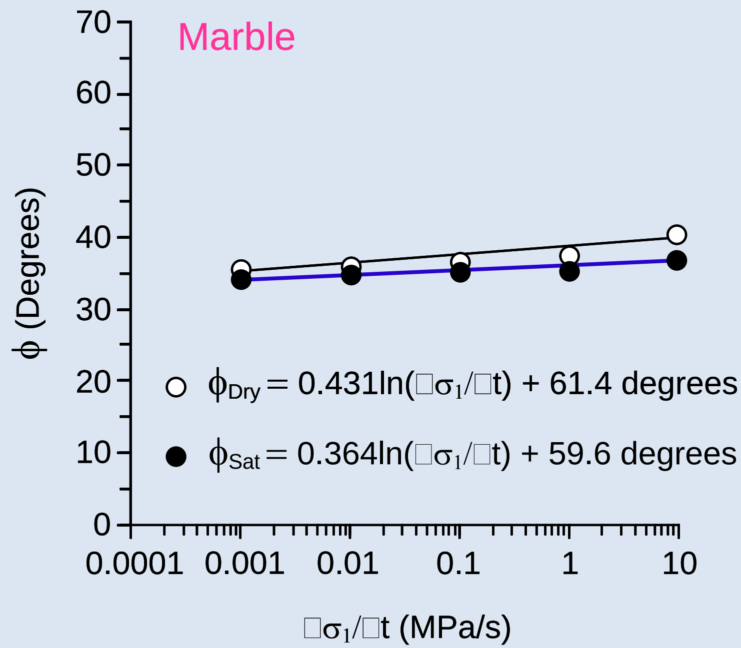


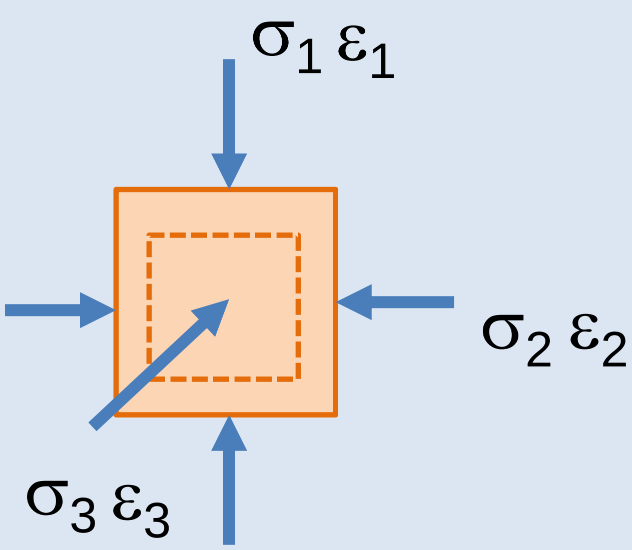




Test Results…

❑ Elastic Parameters

The elastic modulus (E), Poisson's ratio (ν) can be determined by:



$$G = (1/2)(\tau_{oct}/\gamma_{oct}) \quad (8)$$

$$\lambda = (1/3)\,[(3\sigma_m /\Delta) - 2G] \quad (9)$$

$$E = 2G\,(1+\nu) \quad (10)$$

$$\nu = \lambda/(2(\lambda+G)) \quad (11)$$

Test Results…

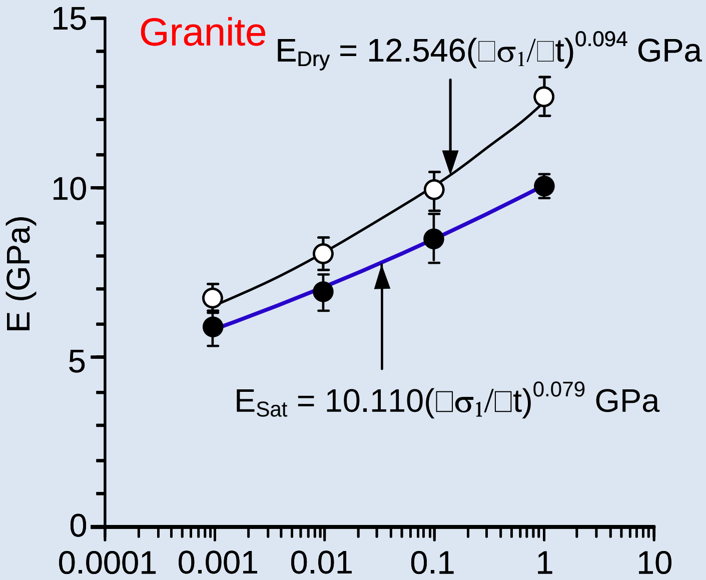
The elastic parameters can be determined as a function of the loading rate as:

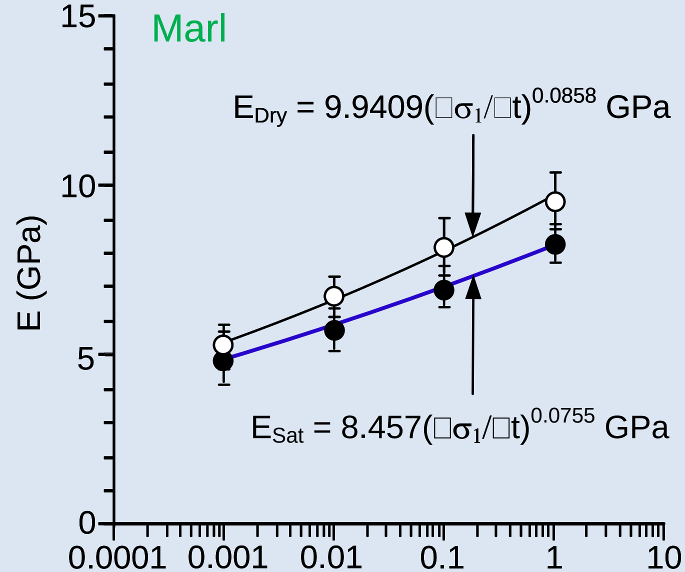
$$E = \kappa \left(\partial\sigma_1/\partial t\right)^{\xi} \qquad (12)$$

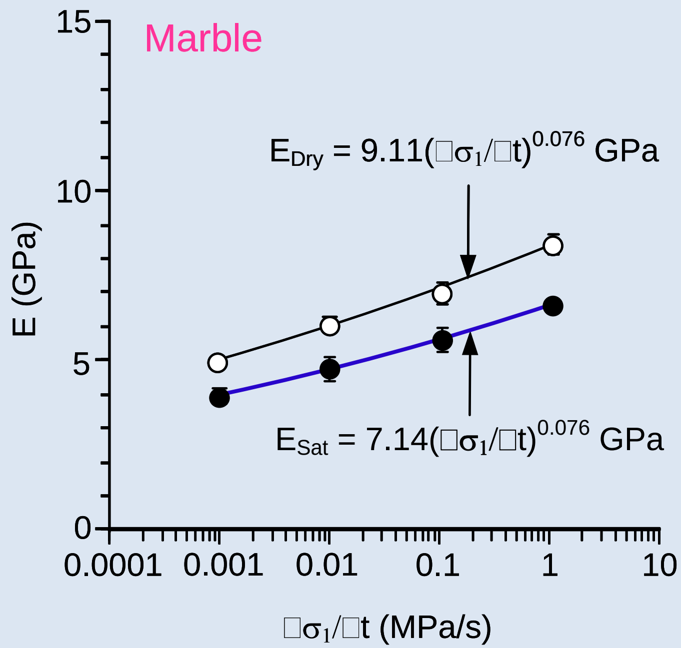
$$\nu = \alpha \ln \left(\partial\sigma_1/\partial t\right)+\beta \qquad (13)$$

The parameters κ, ξ, α, β are empirical parameters.

Test Results…







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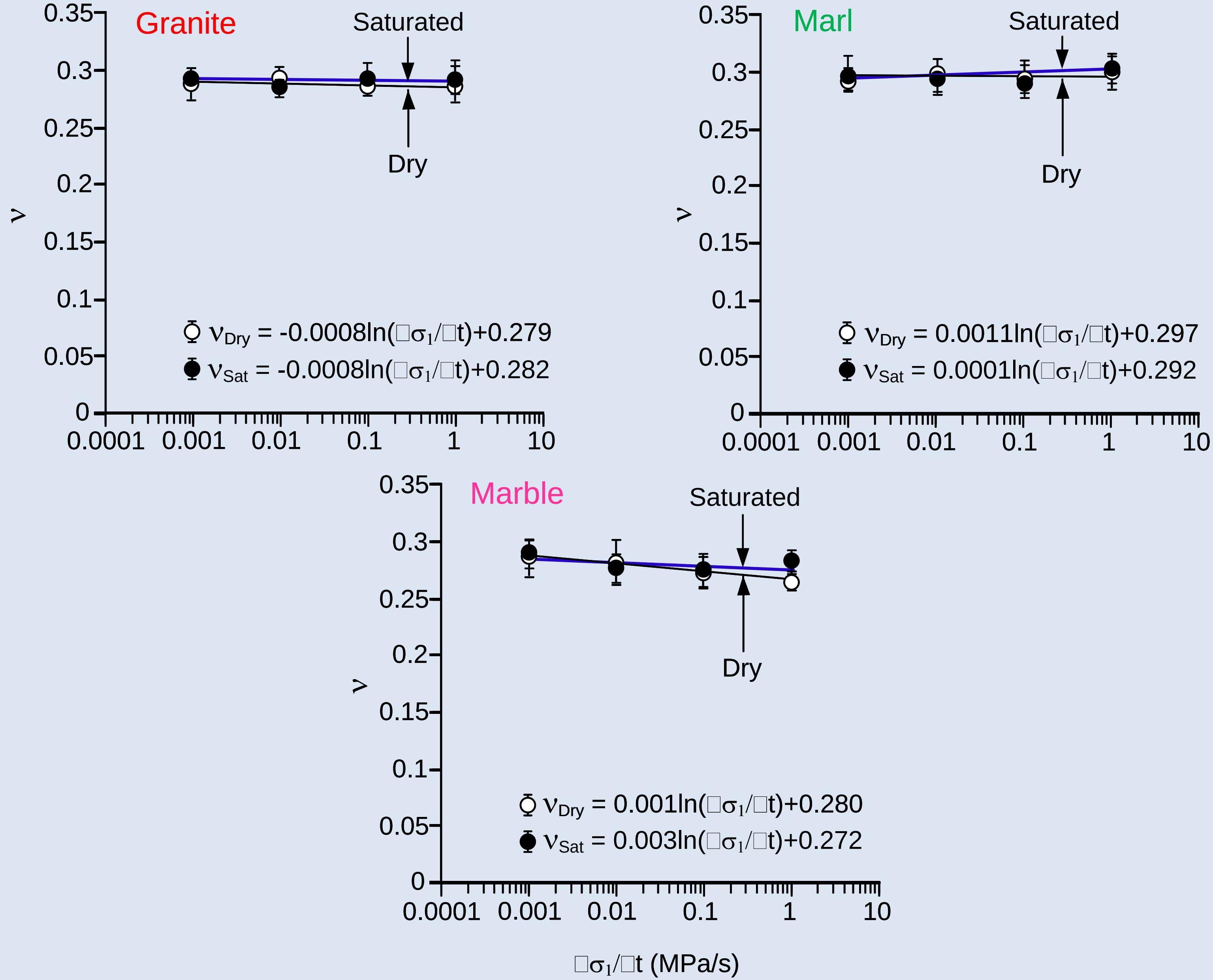
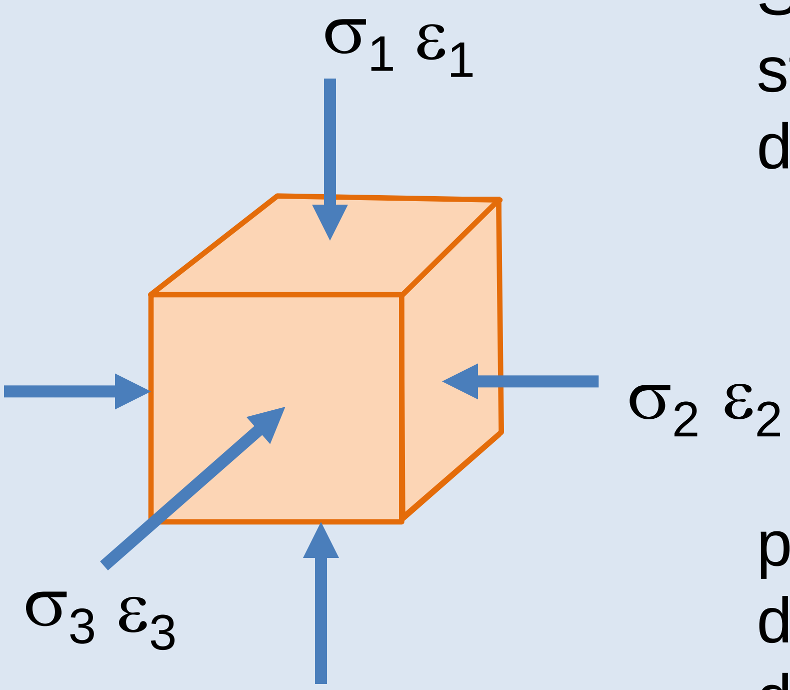


Test Results…

❑ Strain Energy Density Criterion



Strain energy is the energy stored by a system undergoing deformation in 3D.

The strain energy density principle is applied here to describe the rock strength and deformation under different loading rates.

Test Results…

The distortional strain energy (W_d) at failure can be calculated as follows (Jaeger et al., 2007).

$$W_d = \frac{3}{4}\left(\frac{\tau^2_{oct,f}}{G}\right) \quad (14)$$

The mean strain energy (W_m) at failure can can be calculated as follows

$$W_m = \left(\frac{\sigma^2_m}{2K}\right) \quad (15)$$

Test Results…

The elastic parameters G and K can be determined for each specimen using the following relations:

$$G = \frac{E}{2(1+\nu)} \qquad (16)$$

$$K = \frac{E}{3(1-(2\nu))} \qquad (17)$$

where E = Elastic modulus

ν = Poisson’s ratio

Test Results…

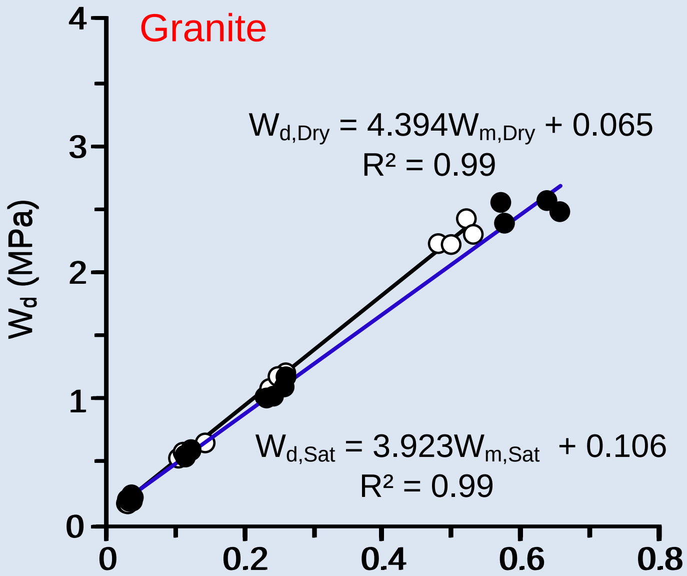
The octahedral shear strength can be determined as:

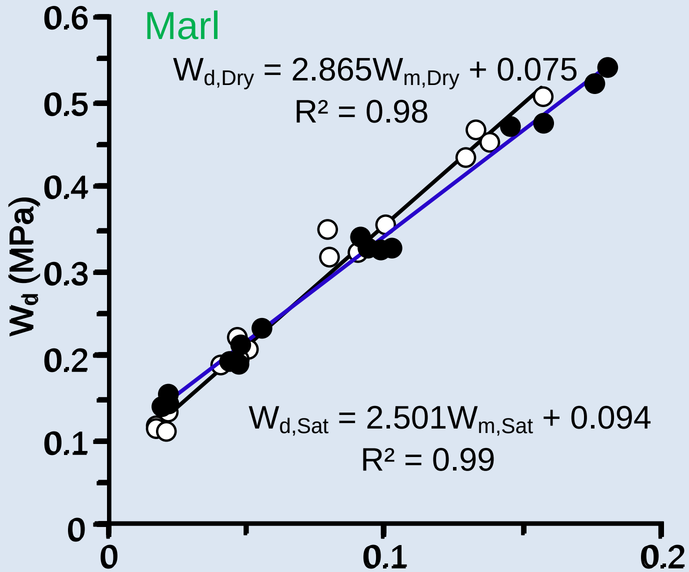
$$\tau_{oct} = [(1/3)[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]]^{1/2} \qquad (18)$$

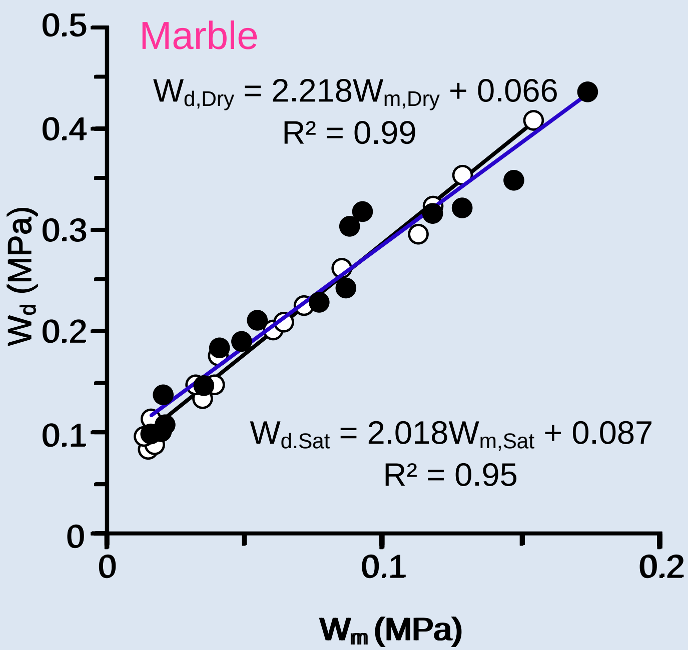
The mean stresses can be determined as:

$$\sigma_m = (1/3)(\sigma_1 + (2\,\sigma_3)) \qquad (19)$$

Test Results…







Summary properties of rock

Parameters	Conditions	
	Dry	Saturated
Compressive strength, σ_1	↑	↓
Elastic Modulus, E	↑	↓
Poisson's ratio, ν	↓	↑
Cohesion, c	≈	≈
Friction angle, ϕ	↑	↓
Distortional strain energy, W_d	↑	↓
Mean strain energy, W_m	↑	↓

Conclusions and Discussion

- The compressive strength of dry specimens is higher than that of the saturated specimens due to effect of pore pressure.

- The strength of rock under low loading rate is lower than of high loading rate because under low loading rate rocks respond to stresses by ductile behavior not brittle behavior.

Conclusions and Discussion…

- The strength of the saturated specimens under high loading rates is reduced the trapped pore water builds up the pore pressure.

- On the other hand, under low loading rates thus the pore water has sufficient time to seep out from the specimens, the rock behavior is similar to dry condition.

Conclusions and Discussion…

- The elastic modulus of the dry specimens is higher than that of the saturated specimens that agrees with Li et al. 2012; Vasarhelyi, 2003.

- The strength criterion can be used to predict the strength and deformation of in-situ rocks under dry and saturated conditions.

Acknowledgements

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